NATIONAL PUBLIC RADIO

Report to the Corporation for Public Broadcasting

Digital Radio Coverage & Interference Analysis (DRCIA) Project: Single Frequency Network Report

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INTRODUCTION

NPR is pleased to present the Corporation for Public Broadcasting this report on Single Frequency Networks for the Digital Radio Coverage and Interference Analysis project. This report – deliverable 6.1.4, as described in paragraph 6.11 of the Scope of Work – covers NPR's experience with this technology over the past few years, as well as the current project for CPB. The following report includes material developed in collaboration with Anders Mattson, a Senior Engineer with Harris Corporation in Mason, Ohio.

Not too surprisingly, a Digital Radio Single Frequency Network (SFN) shares the same properties as Digital Television SFNs, which have already been successful.[1] The main differences between radio and TV SFN are due to the different S/N requirements and guard intervals. SFNs do offer significant potential advantages including better coverage, less interference, less power, higher reliability and a more efficient spectrum use. These properties are derived from basic propagation models. Potential problems that must be considered, and are specific to SFNs, are discussed. They all relate back to receiver performance. In addition, some basic discussion about how antenna patterns can be used to combat delay problems is included. The "hybrid" mode of the HD Radio system has some significant differences in its requirements for SFN distribution since both the digital and analog components must be considered. For a digital-only SFN overlaid on the coverage area of a hybrid FM station, there would still be analog implications to consider. Since hybrid transmission is likely to be the reality for many years to come, it raises special issues that are discussed later in the paper.

ANALYSIS OF SINGLE FREQUENCY NETWORKS FOR IBOC DAB STATIONS

Theoretical Background

According to Information Theory[2] the more energy the more information (bits) that may be transmitted since the bit energy versus the noise power spectral density increases

[1] Anders Mattsson, "Single Frequency Networks in DTV," 53rd annual IEEE broadcast symposium proc, Washington 2003.
[2] The *Fundamental Theorem Of Information Theory*, or just Shannon's theorem, was first presented by Claude Shannon in 1948, and establishes that however contaminated with noise interference a communication channel may be, it is possible to communicate digital data (information) nearly error-free up to a given maximum rate through the channel.

(E_b/N_o). All broadcasters know that the more power one transmits, the better coverage one gets. This has always been understood to mean more power into the same antenna. However, the same effect can be had by sending the extra power to another antenna. In a sense, one can argue that the SFN concept is nothing but more power in disguise. There is some truth to that opinion, but it will be shown that for practical propagation, SFNs should actually cover the same area with less power. The reason is that a SFN allows a more even distribution of the power. So, in theory, adding transmitters, i.e. building a Single Frequency Networks (SFNs), should always improve performance.

Single Frequency Networks (SFNs) are nothing new in radio; they have been around for a long time in analog FM. However, performance has been less than stellar. This poor performance is not due to any inherent limitation in SFNs. In fact, it is because of the lack of equalizers in traditional FM receivers. At the moment the receiver can handle the multipath, SFNs offer many potential advantages. Since all digital systems such as HD Radio® and DRM® already have equalization, the old limitations are gone.3 This opens the door for SFNs. What SFNs have to offer are: flexible coverage, improved coverage, decreased interference, and higher reuse. Since all SFN systems are inherently the same, in particular for TV and radio, much of the theoretical background has been taken from the digital television system experience.

To increase coverage in single transmitter system requires a combination of increased antenna height, increased output power, and/or a different antenna pattern. None of these options might be practical. In this case SFNs can offer an attractive option, easily extending coverage with the simple addition of lower-power transmitters at various sites throughout the desired coverage area. Among their many benefits, SFNs are more flexible in terms of coverage area, superior interference performance and inherently more fault-resistant. Another difference for a SFN or repeater may be control of interference to stations on the same or adjacent frequencies since lower power (than the primary “broadcast” transmitter) to fill areas of poor coverage. The focus is on HD Radio, but the same principles apply to all SFN systems. Three different cases of digital audio broadcasting (DAB) will be considered, of which the first two are very similar: digital-only HD Radio and DRM[4]. The third being hybrid analog-digital version of the HD Radio system.

Multipath and Doppler Shift

No receiver can distinguish between reflected signals from one transmitter versus several received signals from multiple transmitters. To the extent that a system can handle multipath, it is possible to design a SFN around it. Since analog AM and FM receivers do not have equalizers, how do they survive in a multipath environment? How do they

[3] “HD Radio” is an In-Band On-Channel (IBOC) DAB technology licensed by iBiquity Digital Corporation and approved by the FCC and National Radio Systems Committee. DRM (Digital Radio Mondial) is an open-source IBOC platform for shortwave, medium-wave/AM and long-wave digital radio broadcasting approved by the ITU, IEC and ETSI.
[4] EBU-UER, "ETSI ES 201 980 Digital Radio Mondial (DRM); System Specification," 2005.

function at all, since some multipath is always present? The answer lies in the narrow bandwidth in relation to the delay spread. The delay spread being the duration of the RF channel's impulse response. For most practical cases, the impulse response will have died down within 100 μs, often after only a few μs. The net effect is that the received signal will appear to fade in amplitude, i.e. there is no frequency selectivity. This is commonly referred to as "flat fading."

In the case of analog stereo FM, however, the effects of multipath can occur before flat fading is significant. For example, delays of only a few microseconds between the direct and reflected paths can cause audible distortion and crosstalk if the amplitude ratios are small (*e.g.*, less than 1:10). This is because analog stereo is sensitive to sideband distortions farther from the channel center than with monophonic FM modulation, and is analogous to wideband data modulation requiring more equalization against multipath than narrowband data.

If the bandwidth of the signal increases, the fading will become more and more frequency dependent. In the time domain, the effect of non-flat fading is inter symbol interference (ISI), i.e. the bits/symbols start to overlap each other. It is intuitively clear that a small amount of overlap should be fine, but significant amounts will blur the signal. In a digital broadcast system with its higher bandwidth and need for high data rates, intersymbol interference does become a problem.

There are two basic approaches to combat multipath propagation/ISI. One is to design a signal that is robust to reasonable multipath. The second is to have an equalizer in the receiver. Quite often a combination of the two is used, starting with the latter. Since the RF channel can be modeled as a time varying filter, the job of the equalizer is to continuously find the inverse filter and apply it to the received signal. The main problem is generally in the estimation of the filter. This has been, and still is, an area of active research.

The other approach is to use a signal that is inherently immune to multipath. In this respect OFDM signals have become extremely popular. They are used in HD Radio and DRM systems as well as some digital television systems. An OFDM system with N carriers can be thought of as consisting of N narrowband transmitters each transmitting a part of the signal. The resistance to multipath is based on two properties, a guard interval and the use of orthogonal carriers. The actual signals consist of CW carriers, whose phase and amplitude are kept fixed during the symbol time. To make them orthogonal, the spacing must be a multiple of the inverse of the symbol time.

Assuming that the channel impulse response is shorter than the guard interval, the guard interval between the symbols ensures that the intersymbol interference period is longer than practical delay spread. For this reason, many OFDM systems can work in different modes, allowing the user to choose different guard intervals. The frequency response caused by the RF channel will only cause a fixed phase and amplitude offset to each carrier, resulting in each carrier seeing “flat” fading, making them easy to detect. It is worth noting that applying a matched filter to each carrier yields an optimum linear detector, equivalent to taking the FFT on the received signal. This gives the OFDM signal an additional advantage of signal processing with reduced complexity – resulting in lower cost receivers.

As with all systems, there are trade-offs; the guard interval results in a decreased throughput. An OFDM system without guard interval using an equalizer would have a higher throughput. It should also be noted that it is possible to add an equalizer to an analog FM receiver, given the decreasing cost of processing power (DSPs and FPGAs), which might otherwise make analog SFNs much more practical.

Doppler shift

Doppler shift will occur if the impulse response changes over time, for example by the receiver being in a moving car. The net effect is that a reflected signal can be slightly offset in frequency

$$f = f_c \frac{1}{1 + v / v_c}$$

v = Speed of object

v_c speed of light $3 \cdot 10^8$m/s

In a SFN system when moving away from one transmitter towards the other, the frequency difference between the two signals will be

$$f = f_c \frac{1}{1 + v / v_c} - f_c \frac{1}{1 - v / v_c} \approx f_c \frac{2v}{c}$$

For a car on a freeway, worst case, this would be about:

$$100\text{MHz} \cdot (2 \cdot 100\text{km/h})/(3 \cdot 10^8)) = 2/3 \cdot 100/3.6 = 22 \text{ Hz.}$$

In an OFDM receiver without equalizer, the two signals, after taking the FFT, will appear as having a 22 Hz offset. This destroys the orthogonality between the carriers. An alternative view of this degradation is as intersymbol interference in the frequency domain. The question is: how much interference will this cause, and might it cause problems? Assuming that the receivers do a simple FFT of the signal, then the time limited carriers will have a *sin(πx)/πx* type of spectra, where each carrier would be found at x=1,2,3....etc. For FM HD radio signals with a 363.4 Hz carrier spacing, a 22 Hz offset will result in the nth carrier leaking into the first by:

$$\varepsilon_n = \sin((\pi 22 / 263.4 + n) / (\pi (22 / 363.4 + n))$$
$$n = \pm 1, \pm 2, \pm 3, ...$$

Since the different carriers are assumed uncorrelated, the power will be:

$$\sum |\varepsilon_n|^2 \approx 1.1 \cdot 10^{-2} \Rightarrow SDR = 40dB$$

Hence, Doppler shift is not a problem. If someone would be driving really fast, say 200km/h (125mph), the Doppler shift could reach 44 Hz, and the SDR would be 14 dB. For a QPSK signal, this is still acceptable. Note that this assumes that the car is driving on a straight line from one transmitter to the other; in reality this is somewhat unlikely.

It follows that multiple transmitters in a DAB SFN can have quite a bit of frequency offset. A rough estimate is 10 Hz. (By comparison, the ATSC digital television SFN standard calls for transmitters to be within 1 Hz of each other.) The reason lies with the receiver equalizer, which needs to track the two carriers, and in many receivers this happens on a rate of a few Hz. With today's easy access to good frequency references (GPS), it is relatively easy to lock the frequency of two transmitters.

SFN Performance Specific to HD Radio Receivers

As in the normal multipath case, the receiver will work just fine, as long as signals delayed more than what the equalizer can handle will be below the signal to noise threshold - taking some fading margin into consideration. Note that the transition is smooth, so that if a receiver can handle 100 us of delay, it won't immediately break down at 101 µs. Theoretically, what really matters is the bit energy (E_b) relative to the power spectral density of the noise (N_o). Since signal to noise (S/N) is more commonly measured, it is practical to relate the two. Since the HD Radio carriers carry QPSK modulation, one can approximate the S/N needed by relating back to QPSK performance. In turn, QPSK can be seen as two orthogonal BPSK signals, so it is possible to relate back to BPSK performance. Effectively, the E_b/N_o for an OFDM carrier is the same as the S/N of the signal. Half of the QPSK signal energy and half the noise energy is in the I channel and the other half in the Q channel. Thus, the bit error becomes:

$$P_B = Q\left(\sqrt{2S/N}\right)$$

For an S/N of 5 dB, the BER is already down to 10^{-7}, so the signal is inherently robust. The HD Radio waveform has a guard interval of about 156 µs, out of a total length of 2.9 ms. If there is a multipath delay of 78 µs, there will be little overlap within the "core" symbol, and very little ISI. For a multipath delay of 156 µs, the overlap will be 78 µs, where the overlapping signal is gradually decreasing due to the pulse shaping. Hence the S/N due to the overlap will be $10 \cdot \log_{10}(2900/78) = 16$dB. Since this is a good S/N ratio for QPSK, it seems that multipath delays of up to the guard interval of 156 µs, should be acceptable. Ideally it should be less than 78 µs.

Should one allow for a fading margin? Definitely, the different paths will fade independently so a 10 dB fading margin should be sufficient. This only affects delayed signal paths that are beyond 78 µs. For a delayed signal of 156 µs, the S/N will be 6 dB, taking the fading margin into consideration, which is an acceptable interference level.

SFN Implementation Issues

The problems one is likely to encounter are the same as in digital television. Implementing a SFN does take care since there are several potential problems. Simply feeding the same AES data streams to two different transmitters will not work. For a SFN system to work the transmitted signals must be essentially identical and within an appropriate time interval. There are at least three things that can break a SFN system: Timing errors, frequency offset, and non-identical data.

In a SFN system most receivers will receive only one dominating transmitter (in the sense that the other signals are sufficiently weak to not interfere). The only receivers that will experience multiple signals are those where the signals from the different transmitters are within the S/N range of the various systems, e.g., 10-15 dB. Outside this range, the other transmitters can be treated as noise, as shown in Figure 1. Signals from other transmitters outside this range can be used by a receiver with a good equalizer, but they don't have to be. In an OFDM system, all the signals arriving within the guard interval will be used by the receiver. These signals will be used by the OFDM receiver without any need for an equalizer.

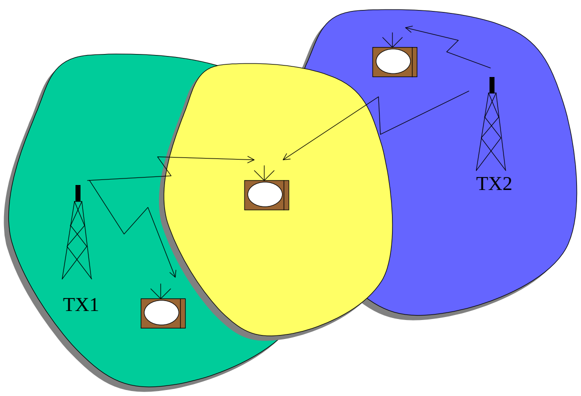

Figure 1 Areas served by the different transmitters

In a SFN system there will always be areas where the signals from two or more transmitters are very close in amplitude, within a dB or less. This will result in some frequencies being notched out. There is nothing that can be done about this. However, it will not break the system; the error correction will handle it (within reason). The problem with signals close in amplitude is less of an issue in OFDM since OFDM receivers do not care if the channel is minimum phase or not. As long as the delayed signal in an OFDM signal are within the guard interval, they will be correlated and will make the RF channel appear to have a more uniform frequency response. A worst case is two signals of equal amplitude with a delay of 75-150 μs, which will result in notches in the frequency response every 13-7 kHz. For an HD Radio signal's 363 Hz subcarrier frequency spacing, there is more or less a 50% chance that a particular subcarrier is significantly attenuated.

Frequency Errors

It was shown earlier that any frequency offset between carriers in an OFDM system results in ISI in the frequency domain. Further more, this frequency offset can be seen as a Doppler shift. As long as the frequency offset is within the Doppler shift bound, the system will work. For both HD Radio and DRM systems this limit is a fairly generous 20Hz (approx). In systems that do use equalizers, the Doppler shift can be tracked out providing the equalizer can be made to track the channel. In OFDM systems without equalizers, the general case, it is not possible to track it out.

Data and Synchronization Errors

Ideally, the different transmitters will transmit exactly the same signal. One way to achieve this is by distributing the actual RF signal using repeaters. If not, the individual transmitters must perform identical modulation. If the individually modulated signals are not the same, the receiver will obviously not work. This is a problem unique to SFN systems. The studio to transmitter link, STL must be error free; if not, this becomes a separate problem.

It might seem that this would be all. However, not all digital transmission standards are deterministic. For example, the input data is often processed in blocks, but where to start is left up to the modulator. Trellis coders might have random initial states, as in the ATSC digital TV standard. Or, if an error occurs in a trellis coder, it might propagate forever. In this case the system is, in some sense, unstable. Furthermore, any training and synchronization sequences must be inserted at exactly the same point. These types of problems are also unique to a SFN. One way to achieve synchronization is to insert some symbol in the data stream. An alternative is to send all, or part of, the modulated data to the transmitter. This simplifies things but might require more bandwidth in the STL.

Data synchronization only becomes a problem if SFN applications were not considered at the system design phase. Once one is aware of the problems of data synchronization, they are easily circumvented at the time of the standard setting.

Delay and Timing errors

The theory behind signal delay is exactly the same for both radio and TV SFNs. This and the following sections up until “Less Interference in SFNs” summarize results found. For the SFN to work the time offset as seem by the receiver must be within the bounds of the equalizer. The time difference between the signals from two different transmitters depends on two factors: the time offset between the transmitters, and the receiver's position relative to the transmitters. If the delay is longer than what the equalizer can handle, there will be problems. Similarly, if the receiver already sees a delayed signal from one transmitter, adding a second or third transmitter etc., which introduces very little extra delay, can potentially put the equalizer over the edge.

Lines of constant time difference turn out to be hyperbolas as seen in Figure 2.

Lines of constant time difference

TX distance is 2c

$o<\alpha<c$ $\alpha=0$ $o<\alpha<c$

$\alpha=c$ $\alpha=c$
$\Delta\tau=2c/v$

TX1 TX2

$$\frac{x^2}{a^2}+\frac{y^2}{c^2-a^2}=1 \Leftrightarrow \begin{cases} x = a\cosh(t) \\ y=\sqrt{c^2-a^2}\sinh(t) \end{cases} \quad -\infty < t < \infty$$

$$\sqrt{(x-c)^2+y^2}-\sqrt{(x+c)^2+y^2}=2a$$

Figure 2 Lines of constant delay.

Given to transmitters at coordinates +/-*c* (per Figure 2) the lines of constant delays are:

$$y = a \cdot \cosh(t)$$

$$x = a \cdot \quad c^2 - a^2 \sinh(t)$$

where *a* is the distance difference, which directly relates to the time difference through $\Delta\tau = a / v_c$.

In a SFN the delays are only important in relation to the signal strength ratio. This can be calculated assuming omnidirectional antennas and that the signal attenuation depends on the distance raised to some power α (propagation constant). Setting the signal ratio from the two transmitters in Figure 1 constant and solving gives:

$$\frac{P_{TX1}}{P_{TX2}} = \frac{\left(\quad (x-c)^2 + y^2 \right)^\alpha}{\left(\quad (x+c)^2 + y^2 \right)^\alpha} = p^\alpha$$

$$\left(x - c\frac{1+p}{1-p} \right)^2 + y^2 = c^2 \quad \frac{4p}{(1-p)^2}.$$

This is the equation of a circle centered at *(c((1+p)/(1-p)),0)* with radius *c((2√p)/(1-p))*. The circular shape does not depend on the attenuation constant α, but the actual signal ratio on the circle does: the higher the attenuation, α, the higher the signal ratio for a given circle in Figure 2.

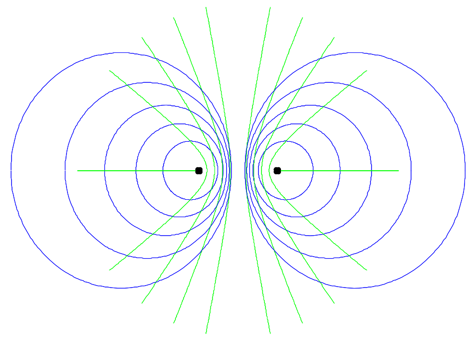

Figure 3 Circles showing constant signal ratio and hyperbolas showing equal delay. The two transmitters are ±c.

In reality, the curves of constant signal ratio will depend on the actual propagation and antenna pattern and could be quite different from circles. The important point is that the curves are generally different from the curves of constant delay. If the HD Radio receiver can handle 78 μs of delay this distance is about 24 km (15 miles), and for 156 μs the distance is 48 km (30 miles). For DRM, the corresponding figures are above 200 km (125 miles).

Far away from the transmitters, the signal strength from the two transmitters will be almost the same. If the distance between the two transmitters is such that the delay is beyond what the receiver can handle one will get a "dead zone" behind the two transmitters, Figure 4.

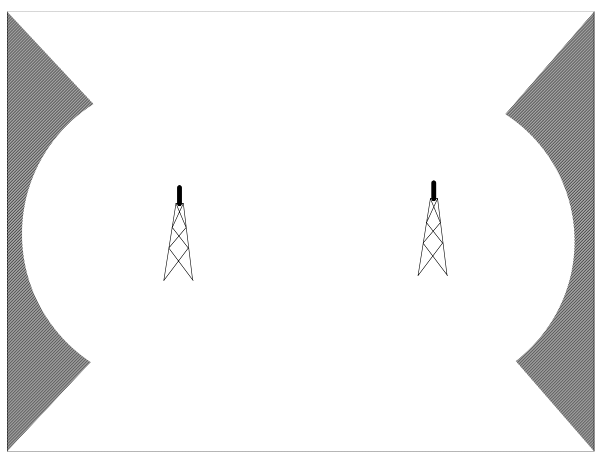

Figure 4 The shaded region shows the area where no reception is possible in a SFN with two transmitters, if the distance between the two is too long.

Depending on the systems, this area, assuming that it exists, might be so far away that it is outside the desired coverage area, in which case the dead zone does not matter. The antenna pattern can be used to combat this problem, which will be covered later.

Transmitter spacing

This is probably the most important issue and depends on the multipath properties of the OFDM signal; and, if present, the abilities of the equalizer. The previous section provides a lower bound on the transmitters spacing. It is obviously desirable to find the maximum spacing. Taking into account that the system can handle some harmful interference (i.e., long delays beyond a certain level) as long as it is below x dB, a less conservative estimate can be found:

$$d = 2c = y_{\mu s} 300 \frac{10^{x/(10\alpha)} + 1}{10^{x/(10\alpha)} - 1} m$$

where $y_{\mu s}$ is the allowable delay in µs, α is the signal attenuation and x is the acceptable interference level in dB. Using x = 15 dB, α = 3, and y = 78 µs, then c = 24 km (14 miles). The maximum distance between the transmitters is 48 km (28 miles), or about twice the distance predicted by using $y_{\mu s}300$.

Power Consumption in SFNs

The power consumption in a SFN, relative to a single transmitter system, depends entirely on the signal attenuation α. For free space propagation (α = 2) they are equivalent, for α greater than 2, the SFN will need less power. The greater α is the more advantageous a SFN becomes. For a SFN with N transmitters the ratio will be:

$$\frac{P_{\sin gle}}{P_{SFN}} = N^{\alpha/2-1}.$$

Note that if α > 2 the overall power consumption in a SFN will decrease as the number of transmitters increase.

Less Interference in SFNs

This is an important property of a SFN. The main reason for this is that the ratio between the closest transmitter and the interferer is greater in a SFN. The calculations are a bit more involved. In essence, the more transmitters used in the SFN and the higher that the propagation constant α , the more advantageous a SFN becomes.

TX Antenna Patterns

Antenna patterns can be used to minimize areas of harmful multipath. If one of two identical transmitters makes a change in its output power the area between the two, where the signals are within ±*x* dB, will decrease, and move towards the transmitter with the lower power. As an example: assume two transmitters have the same output power and omnidirectional antennas, let the distance between them be *d* = 2*c* and let α = 3. Then the region where the signals are within 15 dB of each other occurs at distance of 0.519*c* from each transmitter. In this case, then the signals are within 15 dB in the interval -0.5*c* to 0.5*c*, or about 50% of the distance. If the signal from the second transmitter is 30 dB weaker, this interval becomes 0.5*c* to 0.95*c* or 25% of the distance, as illustrated by Figure 5.

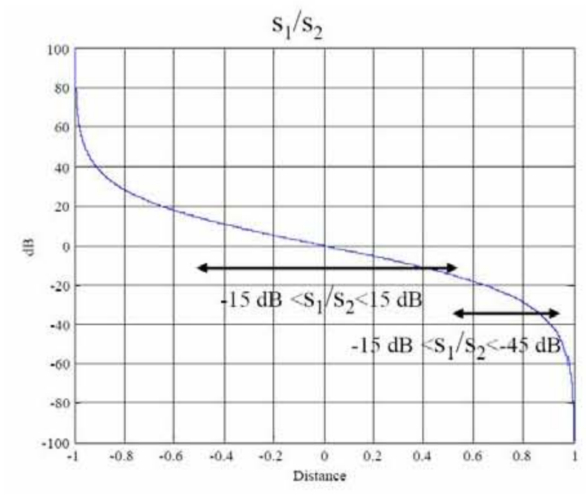

Figure 5 The ratio S_1/S_2 for =1 with one transmitter at -1 and one at +1.

The effect is the same if the transmitters that are away from the center use a directional antenna, where the front-to-back ratio of the antenna provides the power difference. This will decrease the area of harmful interference, i.e., signals outside the guard interval/equalizer range, allowing wider transmitter spacing. Note that the delay between the transmitters must be changed so that zero delay between the received signals occurs in areas where the two signals are of equal magnitude.

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Figure 6 The effect on the area where equalization is needed, thick line, for omni- and directional antennas.

If directional antennas are used, as shown in Figure 6, it is probably better to delay the signals in the two outlying transmitters by the propagation delay. This approach may eliminate the underscored "dead zone" by using an antenna with a front-to-back ratio equal to the S/N ratio plus a suitable fading margin (15 dB for HD Radio signals), Figure 7, but this comes at the price of lower signal strength in the area between the antennas. Adding a third transmitter between the two as shown in Figure 6 can solve this problem. Another alternative is to use four transmitters on a circle with directional antennas and a fifth transmitter in the center using an omnidirectional antenna. In this case, the antenna gain in the directional antennas must be sufficiently low outside ±90 deg in addition to a good front to back ratio. Other configurations are possible.

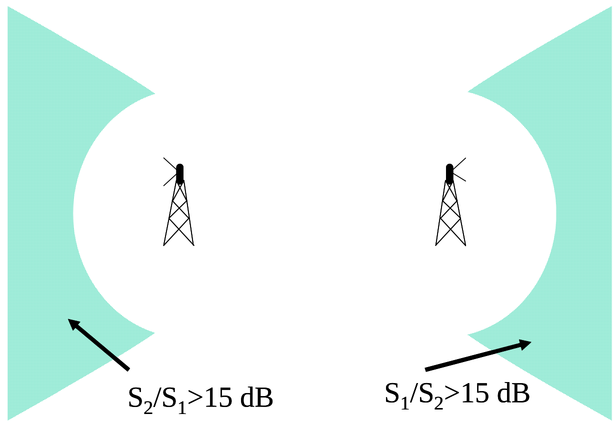


Figure 7 Using directional antenna with sufficiently high front to back ratio to eliminate the "dead zone."

Other Potential Advantages

There are two potential advantages of interest: S/N ratio improvement and diversity. The first one is based on the fact that the sum of two identical signals with independent noise results in a 3 dB S/N ratio gain. In an OFDM system, any signal arriving within the guard interval will improve the signal to noise ratio and is in theory helpful. In a system using equalizers, the S/N ratio gain might not happen due to the equalizer itself adding more gain to parts of the spectrum where the signal is weak. This tends to result in a noise gain. The second advantage is that multiple signals provide diversity. If the receiver sees two signals that are fading independently, the probability that both signals are drowned by the noise is significantly lower than for a single signal. For example, if the probability that one signal is below the noise level is 5%; the probability that both are below the noise level is only 0.25%. However, this assumes the two signals to be independent, which is not the case for OFDM signals when the delay is shorter than the guard interval.

Antenna diversity at the receiver would help, but is only realistic for some receiving situations, such as car radios. A fixed radio receiver would benefit from a directional antenna. Such an arrangement would allow the receiver to change the ratio of the two signals. For a portable receiver, this is unrealistic.

PLANNING AND IMPLEMENTATION OF AN IBOC DAB SFN

A challenge to designing SFNs is controlling the interference between the transmitters. One must predict the signal strength from each transmitter as well as the relative propagation delay times across the desired coverage area. When signal strengths are similar *and* differential delay times exceed a critical value, multipath interference is predicted. The objective is to minimize these areas of multipath or move them to relatively unpopulated places.

In designing SFNs, multipath can be controlled by transmitter site selection, antenna radiation pattern, output power, and modulation time offsets. The site selection is the most powerful, so careful planning of the system is important. Changing sites once the system is built may be expensive or prohibited. Optimizing the antenna radiation pattern and signal delay is possible once the sites are established. Output power should be established once the site is chosen since a 5-10 dB power increase usually requires extensive re-engineering of the other transmission parameters. A power decrease results in a waste of installed transmitter capacity.

No system, SFN or not, will provide 100% coverage. As with all broadcast systems, there will be a tradeoff between coverage and cost. The multipath requirement is the same as for a single transmitter system (i.e., it depends on the system and to some extent what margins are used).

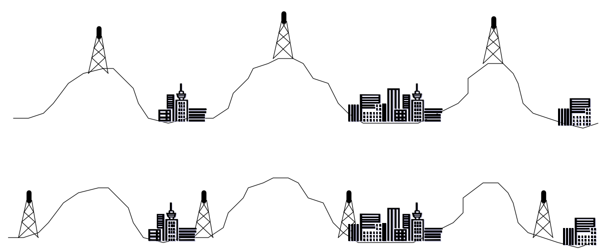


Figure 8 Top: Site location that will increase multipath. Bottom: Site location that will decrease multipath.

In the SFN site selection process the trick is to use the terrain to one's advantage. Figure 8 shows two ways to achieve coverage in a hilly area, with most of the population living in the valleys. With the transmitters placed on the top of the ridges, the risk of excessive multipath is significant. Moving the transmitters down into the valleys eliminates most of the multipath.

Repeaters (also known as boosters) can be used to implement SFNs and they do have one advantage: since the repeater merely repeats the data modulation, the transmitted RF signals will be identical. Even for a broadcast system that can not easily be synchronized due to non-deterministic modulation, repeaters can be used to create a SFN. Repeaters have at least one short coming: their interconnection link adds delay. This is a serious issue since it is often desirable to have zero delay right between the two transmitters. One can employ synchronized transport networks and GPS frequency standards, but the costs may outweigh the coverage benefits offered by the repeater.

The planning of repeaters, boosters and single frequency networks is greatly aided by computer analysis. Computer models can evaluate the field strength ratios and propagation time differentials of the transmitters at millions of local points, a process that would be nearly impossible by hand. Interactive analysis of the location and severity of multipath zones permits the engineer to choose transmission sites and other parameters necessary to optimize a SFN design.

As a case study of SFN design, NPR Labs wanted to evaluate the performance of the first HD Radio single frequency network, built by public radio station KCSN(FM), Northridge, California.[5] This station experiences terrain shadowing effects, caused by the Santa Monica Mountain range that extends along an east-west line in the southern part of their coverage area. This effectively shields Santa Monica, Beverly Hills and Hollywood from service, as shown in Figure 9.

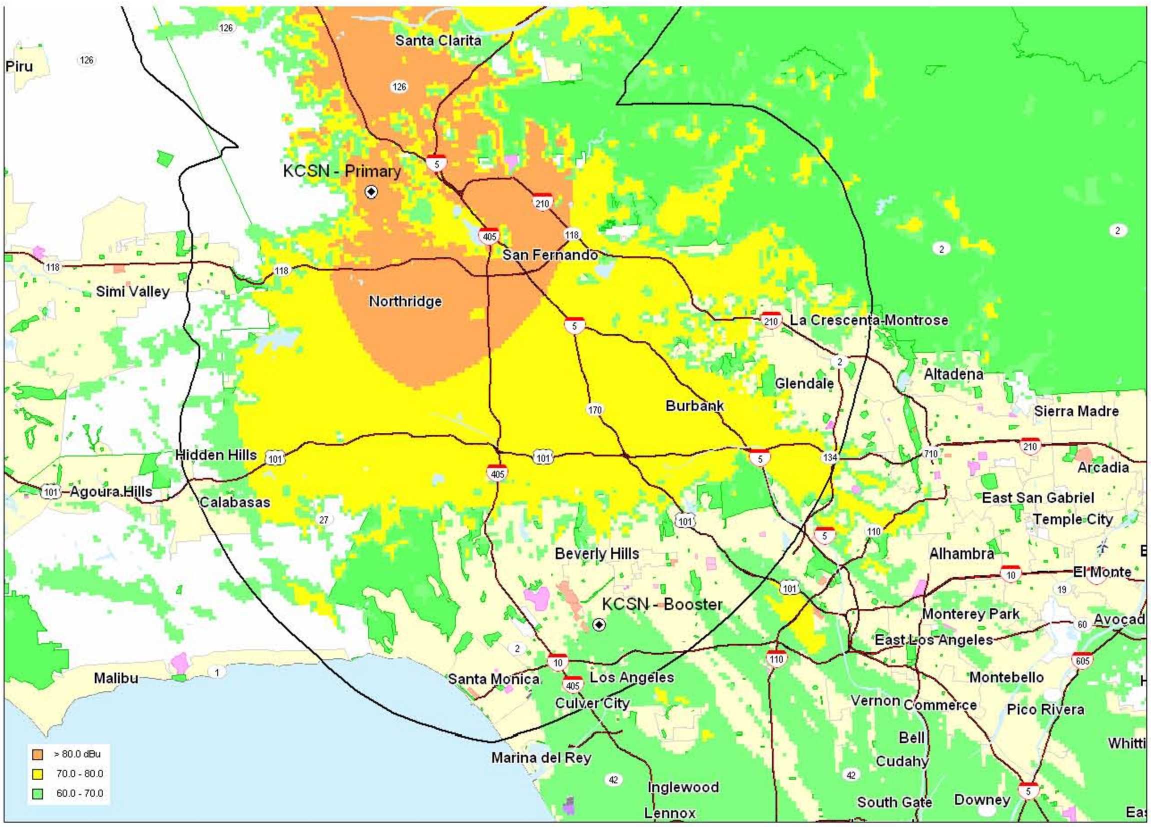


Figure 9 KCSN(FM) primary analog coverage area (part); green is 60-70 dBu. This Longley-Rice coverage prediction shows a sharp cutoff of coverage to the south. Central Los Angeles is in the lower right of the map.

KCSN designed and built a hybrid (analog FM and HD Radio) booster on a building in south Beverly Hills with a directional antenna array aimed northward. This filled in signal in the shielded area, but avoided coverage extension beyond the 60 dBu service contour. The predicted coverage with the booster added is shown Figure 10.

[5] "HD Radio Coverage Measurement and Prediction" 2006 NAB Engineering Conference Proceedings.

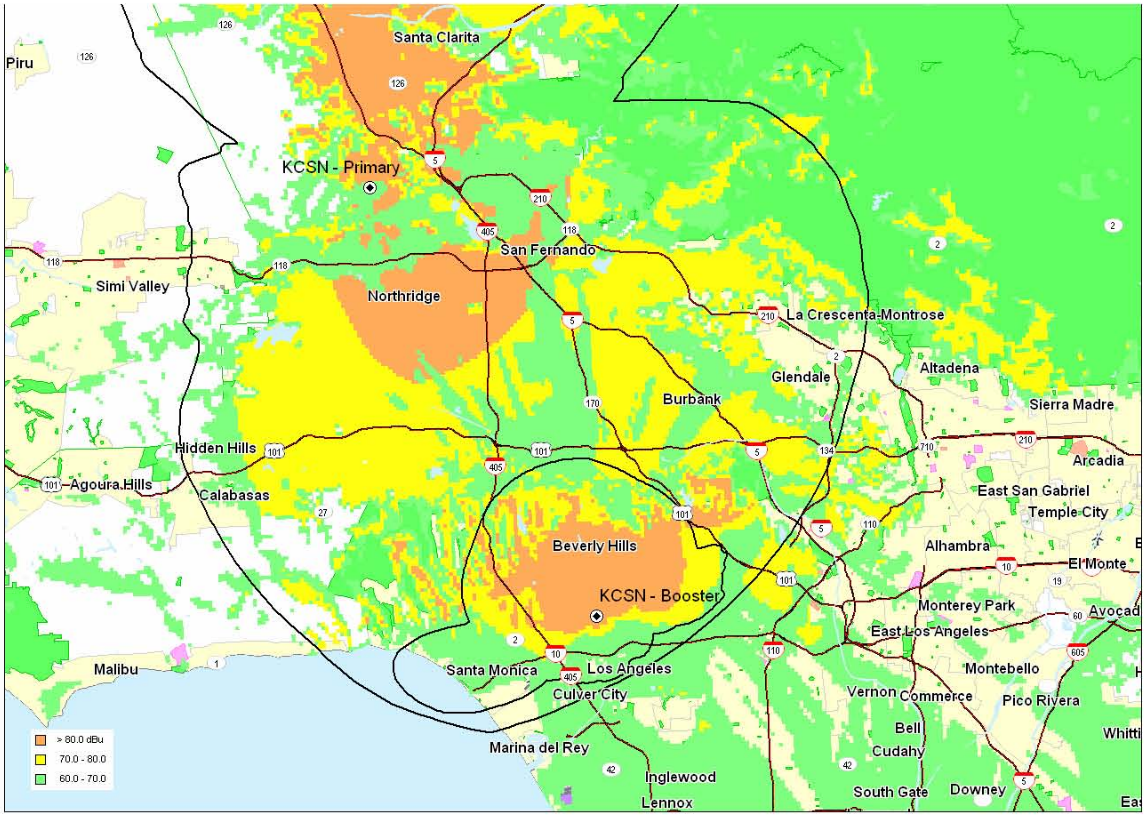


Figure 10 Combined KCSN primary and booster coverage with F(50,50) 60 dBu contours overlaying Longley-Rice field strength prediction.

The KCSN booster and primary transmitter are fed by time-synchronized STLs, so that digital audio is delivered to the inputs of the analog and HD Radio transmitters with differential delay of ±2 µS. GPS is used at both transmitters to control operating frequencies.

To evaluate multipath intersymbol interference NPR developed computer software to model KCSN's two-transmitter SFN. First, the terrain-sensitive coverage predictions were performed in a RF design tool using the Longley-Rice propagation model with 3-arc second resolution USGS terrain data. A receive height of 2 meters was chosen to represent ground-based (especially vehicular) coverage. Land-use land-cover adjustments were used to improve accuracy of predicted fields. Next, numeric arrays containing the propagation study for each transmitter were imported into MapInfo®, a GIS tool, where custom software was developed to:

- Calculate signal propagation time from the primary and booster transmitters to a grid of finely-spaced points across the study area;
- Compare the field strength ratio of primary and booster signals at the same points as above;

- Determine field ratios *and* time-of-arrival differences that may result in intersymbol interference of the HD Radio signals from primary and booster transmitters); and
- Generate a map showing the locations that exceed the parameter guidelines.

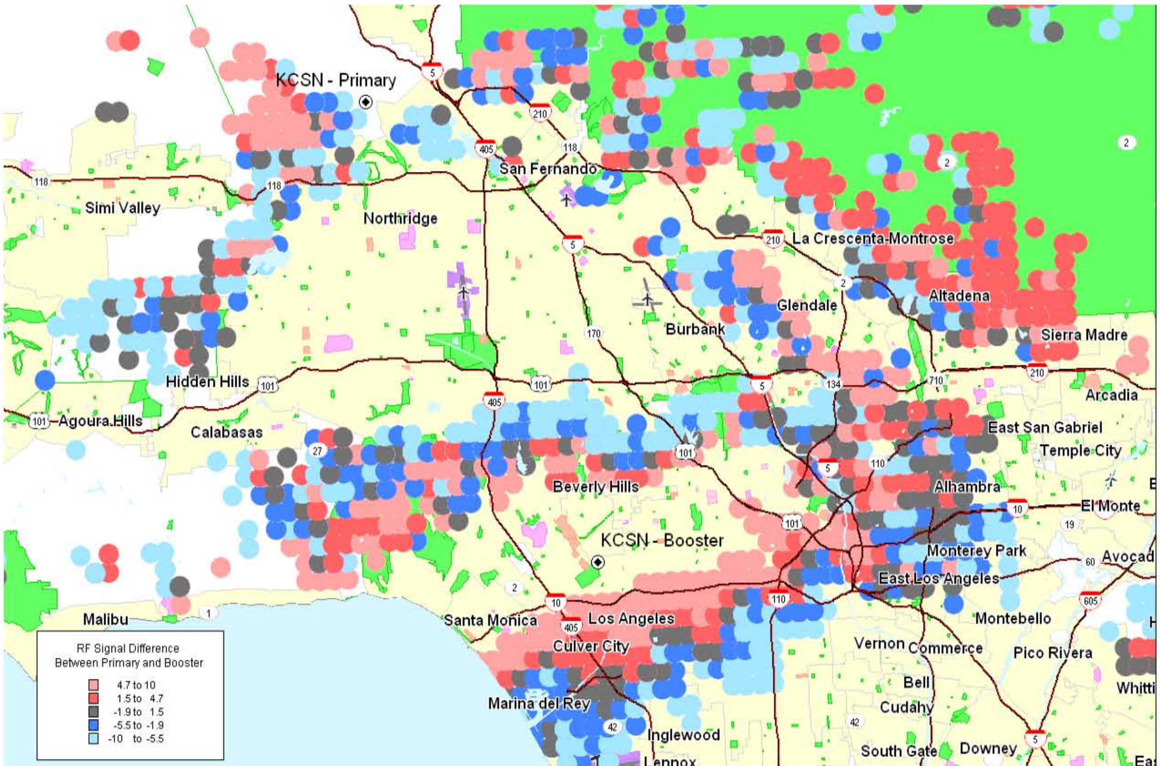


Figure 11 Map showing locations of potentially high primary and booster multipath as colored dots. Reddish dots indicate where the signal from the primary transmitter is stronger and bluish dots indicate where the signal from the booster is stronger; the signal ratios of the gray dots are within 1.5 dB. The rectangular box shows the study area of the measurement test map shown below.

Figure 11 shows the result of the multipath model as a geographic map, where locations of potentially high multipath are predicted. This depiction is based on field ratios within 10 dB and signal propagation difference of greater than 75 µS, as discussed earlier for HD Radio. To eliminate locations that are below practical reception, only field strengths greater than 50 dBu for the stronger signal are shown.

The locations are color-coded to indicate whether the primary or booster signal is stronger, although this is unimportant from a multipath standpoint. It is apparent that the area near each transmitter, where its signal dominates, is free of multipath. A zone of potential multipath rings each transmitter at greater distances, depending on the radiated power, distance and terrain attenuation effects. In the booster's case, the signals mix along the south ridge of the mountains (north of Santa Monica and Beverly Hills) and south of the booster (near Marina Del Rey, Culver City and Los Angeles, which are mostly in the signal fringe).

To evaluate the multipath prediction model NPR Labs used its HD Radio Logger to collect digital receive status, analog field strength, GPS location and time. Figure 12 shows an enlarged portion of the KCSN coverage surrounding the transmitter. The measurement van's drive-test route is shown as a series of small boxes, in which the percentage of local digital reception (as a function of measurement time) is black for 97-100% availability, gray for 90-97% availability and white for less than 90% availability. Most areas experience high availability of digital reception (black squares).

The areas of adequate field strength (blue, green or yellow shading) with low availability (white squares) suggest conditions where intersymbol interference may degrade digital reception. In Figure 12, the areas of low availability appear in East Los Angeles on US Hwy. 101, along Mulholland Drive, north of Beverly Hills and through the canyons of the Santa Monica Mountains on I-405. Comparison with the Figure 11 shows good agreement with these predicted multipath areas. This supports the need to use a multipath model in the design of single frequency networks, to determine the extent and location of intersymbol interference.

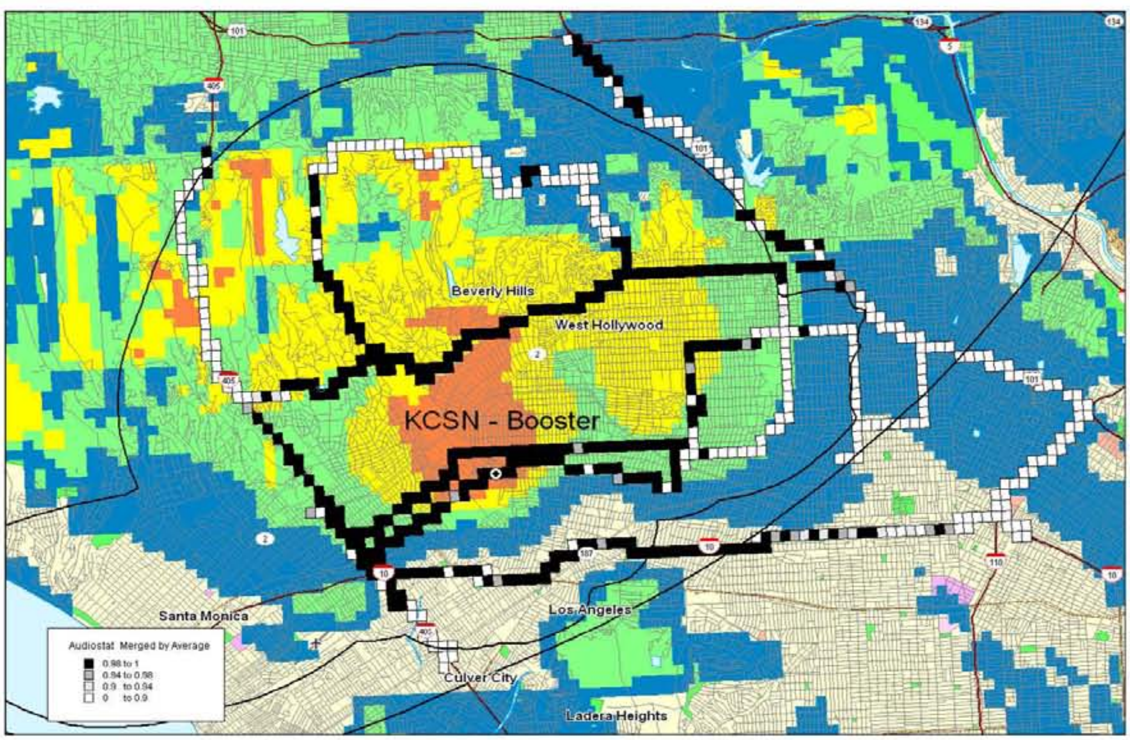


Figure 12 Measurement of HD Radio reception around the KCSN booster. A Longley-Rice field strength prediction underlay shows locations where the booster's field strength is 50-60 dBu (blue) or greater.

Multipath models work well for FM reception using suitable parameters. However, analog stereo has far less tolerance to differential delay than digital systems such as HD Radio. Multipath delays of greater than 1-2 µS will cause audible distortion and crosstalk. The intolerance to multipath begins at field ratios of approximately 20 dB. Consequently, single frequency networks are likely to create large areas of multipath effect with analog FM stereo. Most successful analog SFNs have substantial terrain shielding between the primary and booster transmitters, or the zones of multipath can be shifted to sparsely populated areas.

Issues Specific to Hybrid (Analog + Digital) IBOC DAB Systems

In a system such as hybrid HD Radio using both digital and analog carriers, the whole question about SFNs becomes complicated. As discussed above, the digital part of the signal is not a problem, but the analog part will suffer from the known problems of analog SFNs. (Note that the problem is not a fundamental imitation with analog signal; the problem is that the analog signal, just as many digital signals, requires an equalizer to work in a multipath environment.)

A receiver that can handle digital signals does have the processing power to implement an equalizer for the analog signal. But since existing analog receivers lack one, it is presently a moot point.

FINANCIAL ASPECTS OF SINGLE FREQUENCY NETWORKS

At the time of this writing, no manufacturer has developed repeater hardware for a SFN, making it difficult to accurately determine the cost. However, we have talked with a number of broadcast equipment manufacturers about their concepts of SFN hardware and plans, if any, to produce equipment. Current we have found only one manufacturer that has the scientific and engineering know-how to overcome the technical issues discussed earlier in this paper. They have asked to share their early concepts off-the-record, which we accepted to gain some unique insights.

In a broadcast FM environment, SFNs utilize one or more signal repeaters (also referred to as "boosters"). The repeaters fall into one of two types, discussed below.

Systems That Regenerate the IBOC DAB Signal Locally

These systems locally modulate the IBOC (or optionally the hybrid) RF transmission. This system uses off-the-shelf transmitter technology, and is currently possible; the KCSN repeater in Beverly Hills is a working example. There are several considerations with this system:

- These systems receive audio and control data from the studio, requiring a high-quality data line such as a leased circuit or microwave link. This involves a recurring Telco expense or substantial capital cost, and may limit the choices of repeater location to sites that have Telco access or microwave line-of-sight.

- Regenerative systems must synchronize their data with the primary transmitter (and potentially with other repeaters). This requires hardware to automatically monitor the links to both the repeater and the primary transmitter and maintain the same link delays.
- These systems must synchronize their encoding (modulation) with the primary transmitter. This requires a GPS-derived timing reference, which is already part of IBOC DAB exciters and Importers. However, as discussed above, there is currently no definition in the iBiquity software for time-referenced block coding, potentially resulting in each data block varying from one transmitter to the next. This causes poor receive performance in areas that are subject to overlap between the primary and repeater transmitters. There are no immediate plans to rewrite the Layer 1 software to resolve this problem, according to iBiquity.

As a consequence of the costs and the drawback to overlapped coverage, the regenerative repeaters are less favorable, in our view.

Passive Repeaters That Amplify Off-Air IBOC Signals

This system is fundamentally like an FM translator, which receives, filters, and amplifies the off-air signal, except that the output frequency is the same as the input. This approach is far simpler in concept, but actually harder to implement in hardware than regenerative repeaters.

Because of the multipath-intolerant requirements of analog stereo FM, passive repeaters have seldom proved successful. Since it is rare that terrain shielding can prevent the overlap of primary and repeater signals, it is strongly preferred to remove the FM energy from the repeated signal and retransmit only the IBOC DAB signal. A key difficulty with this is producing a filter that can effectively suppress the FM signal by 40 to 50 dB without affecting the group delay of the IBOC subcarriers. Any differential group delay will result in inter-symbol interference and increase bit error rates. There is no such off-the-shelf filter, and designing such a filter is a formidable task.

Passive repeaters require a wide input bandwidth (more than 400 kHz), which makes them subject to adjacent-channel interference. Since repeaters serve areas of weakened primary station signal, the choices of clear primary reception may be limited, compared the regenerative repeaters that do not rely on off-air retransmission. Also, passive repeaters must guard against signal feedback received from its transmit antenna, which requires opportunistic receive and transmit antenna placement.

According to our manufacturer discussions, the filtering and amplification challenges are being solved and a passive repeater is in the works, reportedly at a price under $30,000. This might result in a budget such as the following:

Table 1 – Cost Estimates for Passive Signal Repeater

Passive Repeater, including antennas and cables	$30,000
RF and design engineering, including geographic and population studies, RF level and time-of-arrival analysis, and hardware specification	$5,000
Construction, including site acquisition and testing	$5,000
Total	$40,000

The recurring costs are principally site lease, electricity and maintenance. It is likely that these costs total no more than a few thousand dollars per year. Remote monitoring could increase the costs slightly.

Output power for a passive repeater, which carries only the IBOC subcarriers, may be limited to an ERP of a few watts for several reasons. For one, signal coordination with the primary transmitter dictates that the repeater no overlap at too great a distance to avoid time-of-arrival interference. Second, although no FCC rules exist for this operation, it is probable that IBOC coverage must be contained within the authorized service area of the primary station, to avoid adjacent-channel interference. Third, the power of a digital-only repeater must be limited to minimize interference to reception of the analog FM from the primary station.

Considering protection against the above side-effects, a digital-only repeater conceivably could cover an area up to 50 square miles for vehicular service and up to 15 square miles for indoor service. By contrast, a primary FM station may cover 1000 to 10,000 square miles for vehicles and 300 to 3,000 square miles for indoor service, depending on station class, terrain and receiver. Those areas do not cover populous locales, in most cases. However, if the shortfall between FM and IBOC signal coverage involved several population centers and several hundred square miles, it is apparent that a minimum of 5 or even 20 repeaters may be needed, per station. This cost could range from $200,000 to $800,000 in capital plus operating costs.

Despite the costs to fill in IBOC DAB service, repeaters are the recommended approach. When properly designed they can provide strategic improvement in communities, especially for indoor service, without aggravating interference to neighboring stations. A simple increase in power ratio, as has been suggested by iBiquity, increases the interference to neighboring adjacent channel stations in an indiscriminate fashion. Increased IBOC transmission power potentially raises the noise pollution around the primary transmitter site, making reception of weaker signals more difficult on many channels; this effect would be especially noticeable in cities, where stations proliferate. Also, our discussions with likely transmitter manufacturers for elevated IBOC power point out that the linear ‘headroom’ required for the IBOC subcarriers will greatly increase the transmitter costs. This construction and operating cost should be compared to the costs for building repeaters for targeted outlying communities.

CONCLUSIONS

Digital radio lends itself naturally to SFN implementations. The main advantage is the potential of very flexible coverage and easy expansion - simply add more transmitters. Depending on the length of the guard interval is, some care will be needed to avoid excessive multipath. The hybrid IBOC system warrants some further studies with respect to the analog part of the signal, before it is clear how well SFN will work in this case. For all other systems, SFN should not pose any fundamental RF related problem. SFNs also present a means for filling in potential IBOC coverage shortfall, relative to FM coverage, in strategic and incremental approach.

NATIONAL PUBLIC RADIO

Report to the Corporation for Public Broadcasting

Digital Radio Coverage & Interference Analysis (DRCIA) Project: IBOC DAB Receiver Improvements Report

Deliverable 6.1.5

CPB Account No. 10446
Reporting Date: January 25, 2008

INTRODUCTION

NPR is pleased to present the Corporation for Public Broadcasting this report on IBOC DAB Receiver Improvements for the Digital Radio Coverage and Interference Analysis project (deliverable 6.1.5 as described in paragraph 6.12 of the Scope of Work). This report covers NPR's experience with consumer receivers and receiver testing during the current project for CPB.

Over the past two years a number of receiver manufacturers have released HD Radio® receivers for IBOC DAB service. NPR Labs has acquired most of them and tested a large percentage of them in our RF lab. These include automotive, table-top and home stereo units in various price ranges. Only portable receivers, which are not yet available, are not part of our inventory. All of the radios have been examined for quality of design and construction, ease of use, general sound quality and reception performance under practical conditions. The combination of objective testing and user experience with the receivers has given NPR Labs an unprecedented perspective on consumer HD Radio products.

Considering the "Coverage and Interference" name of this project, we anticipate that CPB's interest is principally with the aspects of receiver quality that affect the number of potential listeners who will receive a quality service. This paper will focus on our findings that relate to coverage-affecting performance.

PERFORMANCE OF RECEIVERS FOR IBOC DAB RECEPTION

Theoretical Background

As a result of our testing, it has become obvious that a number of different manufacturers, working independently, have produced receivers with surprisingly similar performance, and similar flaws. A look inside the consumer receivers reveals the reason for the similarities : most are built with a common receiver board like the one shown in Figure 1. This small board, less than 2"x4" in size, combines the AM/FM tuner (the module contained in the metal box) with the digital signal processor ("DSP", the large flat-mount IC) and support circuitry for complete tuner board; only a power supply, digital display, tuning and volume controls, audio amplifier, speaker and cabinet are required. The DSP performs the functions of digital IF sampling and filtering, de-interleaver and data and audio decoding. This chip provides these functions for both the analog and IBOC DAB signals.

Figure 1 - IBOC DAB radio system board

The same, or similar, radio system boards are used in many of the current HD Radio receivers, whether they are automotive, table-top or home stereo. It is not surprising, then, that these receivers share some of the same RF performance characteristics, such as sensitivity and interference rejection. In most cases, the manufacturers customize the user interface to support different front panel controls and displays, but these are simply variations in the control software; the RF tuner and IF processing, which is aboard the DSP, is frequently the same.

Nevertheless, we have seen some differences in the behavior of the radios, particularly in the way they handle signal interference. Some receivers react to interference in classic, analog, style, such as increasing interference on an adjacent channel resulting in a gradual and continuously-increasing level of noise, while others exhibit an abrupt shut-down of audio at some level of interference.

Our experience with iBiquity's 1181/1182 radio/development board suggests that there are numerous software-programmable settings for the radio board's operation in the presence of desired and interfering signals of various levels. Consequently, the manufacturers have the opportunity to program a receiver's behavior in ways that affect the outward receiving behavior, sometimes for the worse. In our view, these are merely variations in programming of stock assemblies, and do not constitute an opportunity for "receiver improvements" beyond optimization of configurations.

In general, we have seen little variation in the sensitivity of HD Radio receivers, despite a price range of $100 to $1500. These measurements are bare-channel tests of the "turn on" point in the absence of noise and interference. This basic measurement indicates that under these conditions most receivers come within several decibels of the theoretical sensitivity for IBOC DAB. However, since all of the receivers utilize the Texas Instruments DSP (or a few employ the Phillips DSP), variations in IF sampling and demodulation should be relatively similar. The RF tuner modules that precede the DSP tend to be better than many analog consumer receivers, simply because they have the added job of handling the IBOC DAB data carriers, which operate at only 1% of the analogy host. High sensitivity is a necessary quality to ensure the best receive margins for the digital signal.

Figure 2 - Close-up of tuner section of radio system board

The RF tuner modules are an off-the-shelf product that is added to the receiver system boards, either as a turn-key package for the receiver manufacturers, or added separately by the receiver manufacturer (this would be likely for vehicular receiver manufacturers, who must fit the receiver subsystem into a small dash-mount cabinet with the amplifiers, CD player, etc.).

We have noticed variations in the tuner modules used with some receivers, leading to some variations in interference performance. Figure 2 shows the RF tuner module in the current Sangean HDT-1 component tuner. Five tuned coils are evident inside the metal cage of the module. Considering that this tuner operates on both AM and FM bands, it is likely to use no more than two tuned RF stages before the mixer. Since digital tuning requires varactor diodes, having less “Q” factor than fixed and air-variable capacitors, the amount of RF preselection in this type of tuner is arguably limited. This design presents the mixer with leakage from station signals on frequencies ±3, ±4 and ±5 channels removed from the desired channel. This condition may lead to cross-modulation effects that will lower the effective range of IBOC DAB receivers, relative to receivers with greater preselection. The automatic gain control in this class of receiver will respond to the sum of all signals passing through the RF preselection stages; thus, a strong off-channel signal can push the gain of the receiver below what is optimal for a weak desired signal.

Figure 3 - Tuner module of older radio system board

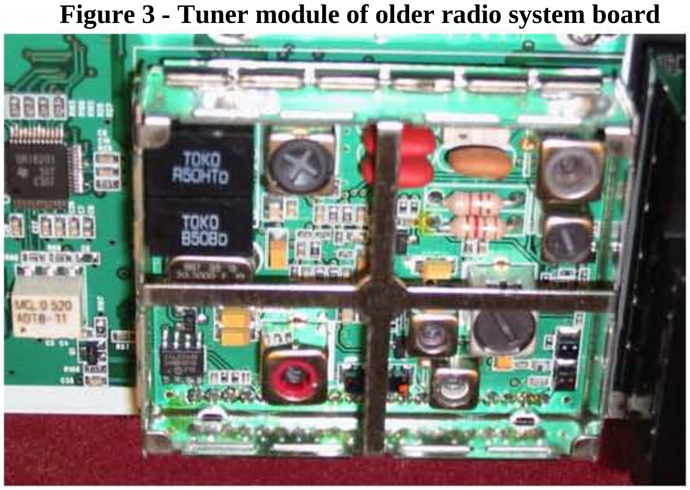


Figure 3 shows the tuner module of an older IBOC DAB receiver, the Boston Acoustics Receptor HD, for comparison. It is apparent that this AM/FM tuner uses one more tuned circuit (6 total) and 5 ceramic filters for AM and FM intermediate frequencies. These added components offer more preselection, both before the mixer and before the A/D sampling in the DSP. It is likely to have better rejection of strong undesired signals, in general, than a tuner module with less preselection.

Other aspects of receiver performance are relatively fixed. For example, the digital decoding and Viterbi error correction are set by iBiquity standard and have fixed C/N and C/I requirements. The iBiquity DSP model, applied by Texas Instruments, already employs universally a patented adjacent-channel interference cancellation technique. More signal processing, if practical, is unlikely if increasing DSP power raises cost (the DSP is usually the single most expensive component in an IBOC DAB receiver).

Conclusion

As manufacturers come under increasing competitive pressure to lower the cost of their HD Radio receivers, our concern is that tuner modules will be <u>cheapened</u>, resulting in reduced preselection and weakened strong-undesired signal performance. This is, of course, not a receiver improvement but a potential lowering of receiver performance. Unfortunately, we see no near-term techniques to improve the reception performance of IBOC DAB receivers, short of the opportunities of production scale to drive down the cost of manufacturing and thereby maximize the quality at a given price point.

One area of improvement that was identified during the first launch of indoor IBOC DAB receivers was antenna quality. Manufacturers initially shipped radios with short-wire (“rat tail”) antennas that were common with analog FM table radios. The lower signal margins, and the potential for the digital circuitry in the receivers to generate noise in their local antennas, drove manufacturers to switch to “T” style antennas, which have higher gain and move the signal pickup farther away from the digital receiver noise. The disadvantage of such antennas is the wall space required and the unattractive appearance of long wires.

We see a need to develop more efficient indoor antennas for IBOC DAB, as well as for future portable receivers. NPR Labs chose a normal-mode helical antenna for its indoor and portable signal tests in this project. Although only 7 inches tall, it performed as well as a whip antenna several times greater in height. A drawback is its bandwidth, which benefits from tuning to the desired frequency. Amplified antennas are becoming more common at radio suppliers, hi-fi and big-box stores. These can offer higher signal gain in a compact and pleasing package (although our previous testing found all of the products subject to severe overloading from stronger signals, thereby negating the advantages of amplifying the weaker signals). Nevertheless, it points out the advantage of new thinking in indoor antennas, which appears to provide the greatest opportunity for receiver improvements at this time.

NATIONAL PUBLIC RADIO

Report to the Corporation for Public Broadcasting

Digital Radio Coverage & Interference Analysis (DRCIA) Project: Report on Potential Effects of Urbanization on IBOC DAB Reception

Deliverable 6.1.7

CPB Account No. 10446
Reporting Date: January 31, 2008

INTRODUCTION

NPR is pleased to present the Corporation for Public Broadcasting this Report on Potential Effects of Urbanization on IBOC DAB Reception for the Digital Radio Coverage and Interference Analysis project (deliverable 6.1.7 as described in paragraph 6.14 of the Scope of Work). This report covers NPR's calculated results and experience from field testing during the current project for CPB.

It is commonly understood that environmental noise affects the quality of broadcast reception and limits the quality of service received by the public. Environmental noise occurs in all locations due to internal receiver noise, atmospheric and galactic sources, etc., but electrical noise tends to rise above these natural sources in populous areas of the world. These man-made sources of noise are increasing as the use of electrical and electronic equipment increases over time. While IBOC DAB signals have a significant advantage under most of these conditions, it requires a stronger signal than analog FM to operate, and the need to avoid frequent signal interruptions, due to the digital "cliff effect," requires a strong signal margin overall. This paper examines the differences in which analog FM and HD Radio® behave in the presence of noise and discusses how these differences relate to environmental noise in urban, suburban and rural areas.

THEORETICAL BACKGROUND

In this section the performance of the analog and digital signals of the FM Hybrid HD Radio system is characterized and compared. The audio performance for the analog signal is characterized in terms of post-detection audio SNR. The digital audio quality is affected by the audio frame error rate, although it can be estimated by the probability of bit error, or Bit Error Rate (BER). The effects of additive white Gaussian noise (AWGN) on these signals are first analyzed to assess relative performance in reception conditions that are generally free of multiple signal reflections (multipath). This is when the receiver in a well-sited stationary location (home receiver), or in a vehicle in an open area where line-of-site or good Fresnel-zone reception dominates. The effects of multipath fading channels (i.e., Rayleigh fading) are also considered in a dynamic channel, such as a moving vehicle without a strong direct signal path to the receiver.

FM Analog Performance in AWGN

The performance of an FM broadcast signal in noise has been previously characterized in the literature using a quasi-static approximation method (e.g., [4]), and a brief summary is presented here. For high pre-detection SNR (e.g., > 13 dB), the performance of FM as a function of its pre-detection SNR in AWGN is

$$\left(\frac{S}{N}\right)_D = 3 \cdot D^2 \cdot \frac{M^2}{2} \cdot \frac{140}{15} \cdot \left(\frac{S}{N}\right)_T$$

Where:

$\left(\frac{S}{N}\right)_D$ is the post-detection SNR in a 15 kHz bandwidth,

$\left(\frac{S}{N}\right)_T$ is the pre-detection SNR in a transmission bandwidth (assumed for FM to be approximately 180 kHz per Carson's Rule: $2\Delta f + f$m),

D is the deviation ratio of the maximum (75 kHz) peak modulation to the maximum audio bandwidth (15 kHz for monophonic FM, for D=5),

$\frac{M^2}{2}$ is the ratio of audio input signal power to peak modulation, such as 0.3 (30%) for broadcast audio.

For monophonic FM case without de-emphasis and D=5 in the equation above, the post-detection SNR gain with 30% modulation according is then 31.5, or about 15 dB. However, this gain is evaluated assuming the pre-detection SNR is in a 180 kHz bandwidth, instead of the 15 kHz signal bandwidth, accounting for about 10.8 dB of the gain using this normalization.

A de-emphasis filter is used at the receiver to improve the SNR. The quasi-static approximation method reveals that the noise power spectrum at the audio output of the FM detector is parabolic and is proportional to the square of the frequency from center. It is therefore desirable to attenuate the increased noise at higher frequencies using a de-emphasis filter.[1] Since a complementary pre-emphasis filter is used at the transmitter the resulting audio amplitude response is flat over a 15 kHz bandwidth. The de-emphasis filter has a frequency transfer function of a 1-pole RC filter with a 3 dB breakpoint frequency at 2.1 kHz. Its magnitude squared characteristic P(f) expressed as a function of frequency (in kHz) is

$$P(f) = \frac{1}{1 + \left(\frac{f}{2.1}\right)^2}$$

[1] *Digital Audio for FM Hybrid HD Radio*, Brian W. Kroeger, 2004, Society of Automotive Engineers 04AE-156.

The noise reduction gain of de-emphasis for the FM monophonic case is

$$G = 10 \cdot \log\left(\frac{\int_0^{15} f^2 \cdot df}{\int_0^{15} f^2 \cdot P(f) \cdot df} \right) = 13.3 \text{ dB}$$

For a sinusoidal audio signal at 30% modulation, then, the overall SNR gain is approximately 28 (15+13) dB.

Using the above equations a receiver with good sensitivity and noise figure of 5.5 dB will yield a SNR as follows:

$$Vi = kTB = 1.38^{-23} \cdot 290 \cdot 1.8^5 = 2.28^{-15} \text{ W/Hz}$$

Where Vi is the noise in a 180 kHz bandwidth, expressed more conveniently as -146.4 dBW/Hz. For an input (receive) power of $5.62 \text{x} 10^{-13}$ (-122.5 dBW) this would yield an RF SNR of

$$SNR_T = \frac{5.62^{-13}}{2.28^{-15}} = 246.9 = 23.9 \text{ dB}$$

Using the initial equation, the audio SNR is

$$SNR_D = 10 \cdot \log\left(3 \cdot 5^2 \cdot \frac{0.3^3}{2} \cdot \frac{180}{15} \cdot 246.9 \right) = 38.9 \text{ dB}$$

With a 13.3 dB de-emphasis gain, the net audio SNR is 52 (39+13) dB. For the psophometric SNR (per ITU-R 468-1) used by NPR Labs for receiver measurements, the audio SNR is approximately 40 dB, which happens to be the target SNR used for determining RF interference ratios. To illustrate the sensitivity of a monophonic FM receiver, a signal power of -122.5 dBW with a half-wave dipole into a matched receiver is equivalent to a field strength of 22.7 dBuV/m.

FM broadcast stereo multiplex transmission incurs a penalty due to the increased input signal bandwidth, *W*=53 kHz. Furthermore, the FM stereo post-detection noise is predominately contributed by the 38 kHz stereo subcarrier signal (L-R) between 23 and 38 kHz, and the pre-emphasis characteristic is no longer matched to the resulting noise spectrum of the stereo subcarrier signal. This gives FM stereo a further preemphasis/de-emphasis disadvantage of monophonic FM. Although the performance of stereo FM without de-emphasis can also be approximated using equation 1, an alternate approach of noise integration yields results that allow evaluation of the de-emphasis gain for FM stereo. In the stereo case, the noise power from 0 to 15 kHz and from 23 to 53 kHz is integrated relative to the original monophonic signal without pre-emphasis. The effects of both stereo and pre-emphasis on the SNR gain relative to FM mono with no pre-emphasis can be expressed as

$$G_{de-emph.stereo} = 10 \cdot \log\left(\frac{\int_0^{15} f^2 \cdot df}{\int_0^{15} f^2 \cdot P(f) \cdot df + \int_{23}^{53} f^2 \cdot P(f-38) \cdot df} \right) = -9 \text{ dB.}$$

From the above, the overall SNR gain for FM stereo with 30% modulation and de-emphasis is 15 dB (mono without deemphasis) minus 9 dB, or about 6 dB. The SNR penalty for converting from FM mono to stereo transmission is then about 22 (28-6) dB. Consequently, the field strength requirement for the same audio SNR describe above would be 22 dB higher than 22.7 dBu, or 45.7 dBuV/m.

Digital Performance in Gaussian Noise

Studies of HD Radio conducted by the Advanced Television Test Center for the National Radio Systems Committee established a carrier-to-noise requirement (Cd/No) for fixed and mobile reception conditions.

Figure 1 - Effect of RF carrier-to-noise ratio on digital errors.

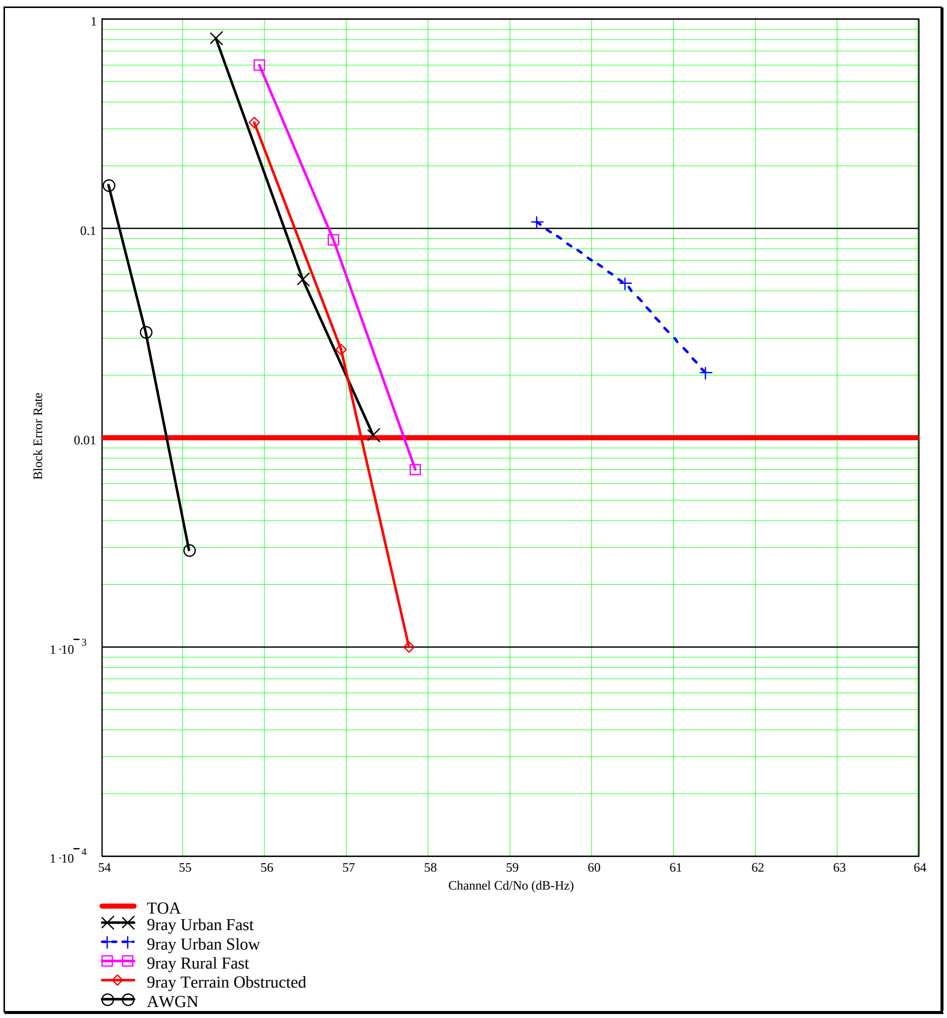


Figure 1 shows the block error rate of the HD Radio receiver (on a scale of 1 to 1×10^{-3}) over a Cd/No range of 54 to 64 dB. The red "TOA" line indicates the threshold of audibility, deemed to be at 0.1% BER. The graph lines indicate the BER performance with AWGN and with 9-ray Raleigh fading for the following conditions: urban fast, urban slow, rural fast and terrain-obstructed paths. Point to the right indicates a higher Cd/No, meaning a higher signal level is required.

Table 1 summarizes the data displayed in the chart. Differences from the reference condition (Gaussian noise) are shown on the right.

Table 1 - Summary of carrier-to-noise requirements for digital receive impairments.

Test	Cd/No (dB-Hz)	Fading Type	Block Error Rate	ΔGaussian (dB)
Gaussian Noise (No Fading/ Interference)	54.1		0.16	
	54.5		0.032	
	55.1		0.0029	
9-Ray Fading	55.4	Urban Fast	0.8	
	56.4		0.056	
	57.3		0.012	2.2
	59.3	Urban Slow	0.106	
	60.4		0.054	
	61.4		0.0202	6.3
	55.9	Rural Fast	0.6	
	56.8		0.087	
	57.8		0.007	2.7

The receive requirements for HD Radio are compiled in the link budget of Table 2. This table computes Vi, the thermal noise of the receiver bandwidth:

$$V_i = 10\log(kTB) = 10\log\left(1.38 \times 10^{-23} \cdot 290 \cdot 70{,}000\right) = -155.5 dBw$$

To the receiver thermal noise is added the noise figure of the receiver, assumed here to be a very good 5 dB, and the carrier-to-noise ratio (*CNR*) taken from the requirements for 9-ray urban fast fading, to produce the required input power for HD Radio. NPR Labs' convention for measurement and mapping is to reference the analog FM host signal, therefore the input power is adjusted by 20 dB to reflect the 1% IBOC-to-analog transmission power ratio.

The link budget converts the signal power to a field strength, assuming a standard half-wave dipole at 90 MHz. (Since most public radio stations operate in the Reserved Band, from 88 to 92 MHz, 90 MHz represents an average for this majority.) The field strength may be modified by various loss factors, although none were applicable here. The result is the incident field strength required for the above-described conditions before adjustment for environmental noise.

Table 2 - Link budget for vehicular reception of HD Radio.

Field Strength Requirements for Vehicular IBOC			
E	= minimum acceptable field strength at a receiver, in dBuV/m for analog host		
	= *Vi* + *Nr* + *CNR* - *IBACr* + *Kd* - *C* - *G* + *L* + *Lf*		
Nr	noise figure of receiver input	5	dB
k	Boltzmann's constant	1.38E-23	W/K/Hz
T	reference noise temperature	290	degrees K
B	noise equivalent bandwidth of input	70000	Hz
Vi	thermal noise of receiver bandwidth	-155.5	dBW/Hz
	thermal noise of receiver input with *Nr*	-150.5	dBW/Hz
CNR	minimum CNR for acceptable service		
	(9-ray terrain-obstructed for TOA)	57.3	dB-Hz
	required input power	-93.2	dBm
	1% IBAC ratio	-20	dB
	required analog host FM power	-73.2	dBm
f	frequency of operation	90	MHz
Kd	dipole factor [$20\cdot\log(9.73/(\lambda\sqrt{G})$]	7.2	dB
C	dBm (50Ω) to dBuV conversion factor	107.0	dB
	antenna gain relative to dipole	-6	dB
L	transmission line loss	0	dB
Lf	location variability factor	0	dB
		47	dBuV/m
	Required field with environmental noise		
F	ITU-R model, noise above *kTB*: $F = c - 27.7\cdot\text{Log}(f)$		
	where *c* = 76.8, business	67	dBuV/m
	72.5, residential	63	dBuV/m
	67.2, rural	58	dBuV/m

The adjustment for environmental noise is based on recognized ITU recommendations that have been updated and verified by ITS studies.[2] Several other studies were consulted in this project, to affirm the general findings.[3] [4] [5] A recognized ITU-R model for predicting environmental noise calculates the noise power present for 50% of the time and 50% of the locations as a function of frequency:

[2] *Man-Made Noise Power measurements at VHF and UHF Frequencies*, Robert Achatz and Roger Dalke, Institute for Telecommunications Sciences, Boulder, Colorado, NTIA-ITS Report 02-390, 2001.
[3] *Clutter Losses and Environmental Noise Characteristics Associated with Various LULC Categories*, Thomas Rubinstein, 1998.
[4] *A Comparative Investigation on Urban Radio Noise at Several Specific Measured Areas and Its Applications for Communications*, Ming-Hui Chang and Ken-Huang Lin, 2004.
[5] *A Report On Technology Independent Methodology For The Modeling, Simulation And Empirical Verification Of Wireless Communications System Performance In Noise And Interference Limited Systems Operating On Frequencies Between 30 And 1500 MHz*, Telecommunications Industry Association TR-8 Mobile and Personal Private Radio Standards Committee, 1997.

$$F_{am} = c - d \cdot \log_{10} f$$

Where

c = 76.8, 72.5 or 67.2 dB for business, residential and rural areas, respectively, and

d = 27.7 dB/MHz.

Impact of Environmental RF Noise

It is noted that some studies suggest that this equation is representative of urban/business and rural environments, but may overstate the noise for suburban areas. This reinforces our primary concern with urban/business environments. There are some precautions about adjusting coverage according to environment that should be noted, however. The difference between urban and rural field strength requirements in Table 2 is only 9 dB, and suburban noise impairment should fall somewhere between the two, but may be only a few dBuV less than the urban field strength.

Rubenstein's study of environment noise by LULC categories indicated only 3-4 dB between all categories, suggesting that use of LULC categories is not a strong means for adjusting coverage. We know from experience that noise degradation is very case-specific (local), such as emissions from dense traffic, overhead power lines, electrical machinery, etc. Based on these factors, we find that geographic prediction or adjustment of IBOC DAB coverage according to environmental noise levels is of limited accuracy and reliability. NPR Labs' field testing of 10 public radio stations across the U.S. indicate that when the measured coverage differs from the prediction model, service usually extends beyond the prediction – possibly due to pessimism on the part of the point-to-point path loss model. These areas are usually open highway through rural areas, which should experience higher than average field strength and lower environmental noise. However, in our examination of drive-test measurements we see little evidence of under-prediction of coverage when routes pass through towns and business areas.

On the other hand, our measurement data confirms that station interference is the stronger predictor of, or lack of, IBOC DAB service. Our examination of station maps indicate that the difference between noise-limited coverage (which is always shown on our CPB maps) and interference-limited IBOC coverage is a pronounced effect. Aside from terrain shielding effects, for stations that are unfortunate to have closely spaced adjacent-channel neighbors the effect of signal interference strongly outweighs other factors.

A note about indoor and portable reception and environmental noise is called for. We have reported in the past on the emissions of digital noise from some HD Radio receivers causing impairment to their own reception of IBOC DAB. This is a serious problem that we trust manufacturers are learning to avoid in subsequent generations of receivers. It also points up the issue of local noise from other sources in the home and office that may affect IBOC DAB reception. This phenomenon is local and to some degree within the control of the listener by relocating their receiver or antenna to optimize reception. At this time we do not propose to make an overall adjustment to shrink coverage to account for this possibility, in addition to adjustments for median building penetration loss with added standard deviation at the 80th or 90th percent of locations. Nevertheless, the margin for signal reception indoors is a concern.

The chart in Figure 2 shows the audio signal-to-noise ratio of monophonic and stereophonic FM versus RF carrier-to-noise ratio, based on the equations discussed earlier. It is apparent that there is a straight-line relationship (dB for dB) from the maximum SNR of the receivers of the left to the threshold of quieting on the right. A dashed line is added to show how some receivers with stereo blend features may improve the SNR, at the expense of stereo separation. This technique effectively increases the sensitivity of the stereo receiver.

Figure 2 - Audio SNR of monophonic and stereophonic FM versus RF carrier-to-noise ratio. Also shown, (in green) is the failure point of IBOC DAB normalized to 1% power ratio.

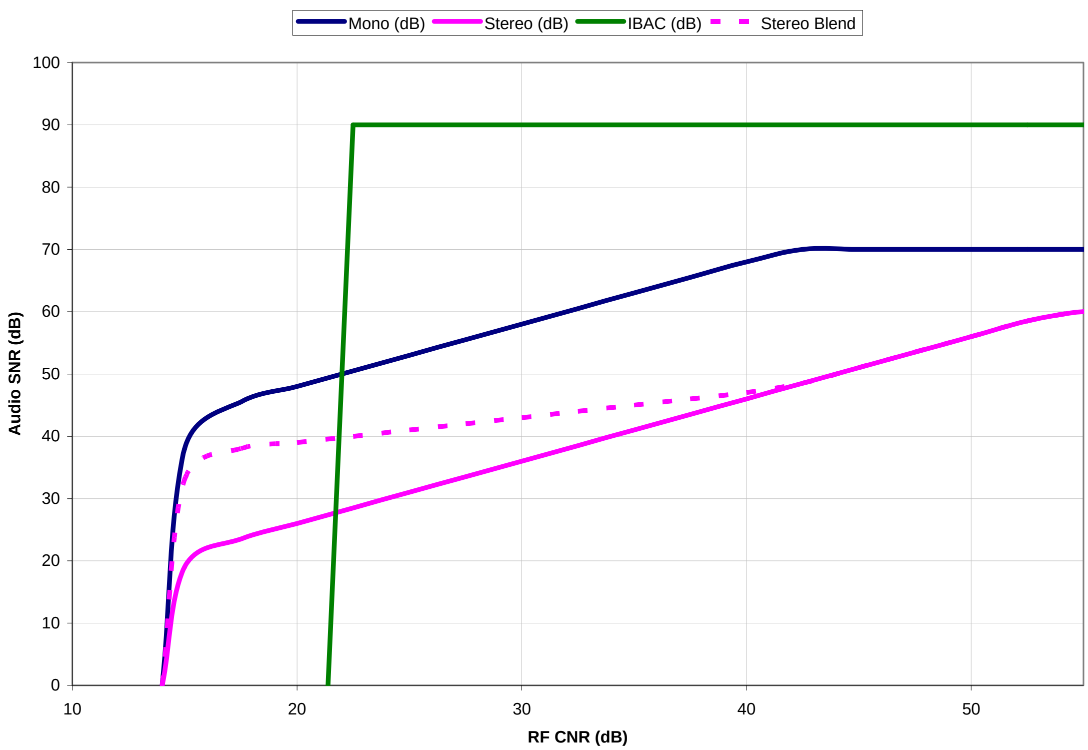


Figure 2 also shows the behavior of an IBOC DAB receiver according to RF CNR. While this system is capable of operating at a CNR of approximately 3 dB, its position on the chart has been adjusted to recognize its operation at 1% of the analog host power. It is apparent that the digital reception ends abruptly at a CNR of around 23 dB, while analog reception still has 10 dB of faded reception left. Because of the "cliff effect" of digital reception it is necessary to add a larger margin to the minimum received signal to avoid dropouts. This additional margin has the effect of shrinking the service area, which is reflected in our coverage prediction maps.

NATIONAL PUBLIC RADIO

Report to the Corporation for Public Broadcasting

Digital Radio Coverage & Interference Analysis (DRCIA) Project: Performance Evaluation of FM Indoor Receiving Antennas

Deliverable 5.6 (Per ¶ 6.8 of Attachment A, Scope of Work)

CPB Account No. 10446
Reporting Date: 12 February 2008

INTRODUCTION

NPR is pleased to present the Corporation for Public Broadcasting this interim report on the Performance of FM Indoor Receiving Antennas for the Digital Radio Coverage and Interference Analysis project. This report covers NPR's experience with commercially available antennas designed for use with domestic radio receivers during the current project for CPB.

GENERAL BACKGROUND

Satisfactory radio reception is dependent upon the performance of a chain of items—including the transmitter, transmitting antenna, propagation environment, receiving antenna and radio receiver. The performance of any radio receiver can be no better than the signal delivered to its circuitry, and at the consumer end this is directly influenced by the quality of the receiving antenna used.

In the early years of FM broadcasting, it was common for the consumer to use an outdoor antenna for signal reception. Numerous brands and models of dedicated FM receiving antennas were available, and some consumers made use of their VHF television receiving antennas—which were also commonplace in urban and rural areas—for FM reception. Nearly every FM receiver offered antenna input terminals, and many receivers were sold bundled with simple indoor antennas—typically 'T' dipole antennas—intended to be tacked to an interior wall in the vicinity of the receiver.

As the number of FM stations, FM receivers and FM listeners grew, inexpensive mass-market radios were manufactured with various forms of built-in receiving antennas, sometimes a simple length of wire dangling from the back of the receiver and often an invisible coupling to the radio's power cord. Connecting terminals for external antennas disappeared from many or most inexpensive models, with such terminals becoming associated with relatively expensive 'higher end' radios and component-level tuners and receivers.

The advent of IBOC DAB radio receivers has at least temporarily reversed this trend, at least within the limited constellation of HD Radio receivers. To the best of our knowledge, every commercial HD Radio receiver is designed to accommodate an external antenna, and every such radio is delivered with an 'accessory' receiving antenna of one type or another. The reasons for this are probably twofold: reliable indoor HD Radio reception is clearly more difficult to achieve than traditional FM analog reception and appears to be possible over a smaller geographic area; and the current generations of HD Radio receivers are relatively expensive (at least when compared with mass-market models), closer in cost to 'higher end' analog receivers that consumers might be expect to purchase for use in locations with less favorable reception.

RENEWED INTEREST IN RECEIVING ANTENNAS AND EARLY TESTS

In the earliest days of domestic HD Radio receiver availability (ca. late 2005, following the introduction of the first widely available tabletop HD Radio receiver), public radio station managers and technicians commented to NPR Labs staff members about their observations regarding apparent limitations of FM HD Radio coverage and the seeming inadequacy of the receiving antennas supplied with receivers. This propelled NPR Labs to acquire a number of commercially available receiving antennas, and to test them informally within NPR's headquarters building. Results of this work were published on 16 February 2006 in NPR Labs *IBOC Field Service Bulletin No. 02.20060216* "Indoor FM HD Radio Antenna Performance," attached as Appendix A.

Four antennas, two compact powered (active or amplified) units and two passive antennas were evaluated. Analysis of the RF spectrum delivered by these antennas using a Hewlett Packard 8630A Spectrum Analyzer revealed that, with received signal levels of low to moderate strength, the active antennas delivered signal levels higher than simple passive antennas but with higher background noise levels, as well; apparently, thermal noise and intermodulation products generated within the active units' gain stage(s). This resulted in the observation that some active antennas delivered significantly poorer FM carrier RF signal to noise level ratios than simple, less expensive passive antennas. The implied conclusion of the Field Service Bulletin was that, <u>in areas of moderate signal strength, inexpensive passive antennas would be likely to deliver better in-building performance</u> than the two (unidentified) active antennas. The report concludes with the observation that further testing of indoor receiving antennas would be desirable.

TESTING CONSUMER INDOOR RECEIVE ANTENNAS

With the understanding that the largest portion of the U.S. population lives in or near urban areas and the belief that much of that population will by motivated to use indoor receive antennas (as opposed to traditional high-performance rooftop antennas), we decided to conduct our tests in an urban and a suburban environments. For convenience, cost and expediency, we chose to do our testing in the metropolitan Washington DC area rather in the controlled conditions a formal antenna test range.

Testing FM reception in a real-world environment can be challenging. At FM broadcast frequencies, signals are reflected by innumerable objects, both natural and man-made, and at a given location it is difficult to determine the relationship between a signal arriving directly from the transmit site and time-delayed reflected signals arriving from other directions. Since the reflected signals invariably degrade the reception of the direct signal, there is an incentive to find test locations that minimize this phenomenon.

NPR Labs is fortunate to have found one such location within a few miles of its headquarters that meets these needs. Public radio station WAMU-FM (88.5 MHz) and commercial stations WASH-FM (97.1 MHz) and WRQX (107.3 MHz) all have transmitters located within less than 1.25 miles of one another in Northwest Washington DC. These are nearly directly opposite an accessible public location on the west (Virginia) side of the Potomac River which offers a direct view of their antennas and terrain which affords essentially free-space reception of those signals with relatively few early reflections. This location is hereafter identified as the ‘Potomac Overlook’ site. Appendix C provides a photographic view of the towers from this site and illustrates the terrain profiles from the three transmitting locations to the Potomac Overlook site. Received signal level measurements of WAMU-FM at this location yielded results which match well (within approximately one decibel) with RF levels predicted by signal propagation software utilizing an advanced integrated terrain model. The RF levels observed at this location are high, but in line with what might be expected of real-world reception conditions near urban transmitter sites.

A second measurement site in Fairfax County, Virginia, approximately 20 miles from the three transmitters, was selected to examine antenna behavior in a suburban environment, representing more modest received signal levels. Terrain at this site (it is the highest point in the county and is devoid of nearby foliage and structures) also could be expected to minimize the number and strength of early reflections. (Terrain profiles for the Fairfax site were not pertinent since the paths to the three reference FM stations were below the intervening terrain and clutter and not free-space paths.) This location, however, demonstrated and unexpectedly high received signal level from a commercial FM station (WJFK-FM 106.9 MHz) located just over eight miles from the test point. (The station transmits a highly directional signal focused toward a rapidly developing area beyond the test site.) Significant RF overload performance was experienced with some of the tested antennas, but this too could be considered to be similar to reception conditions expected by many listeners.

TEST METHODOLOGY

A relatively simple test methodology was developed. A tunable “reference dipole” antenna, the Potomac Instruments model Ant-71, with calibration data traceable to the National Institutes of Standards and Technology, was used with an industry-standard Potomac FIM-71 VHF RF signal level meter to measure the received signal level of the three “reference” FM stations at a point approximately nine feet above ground at both the Potomac Overlook and Fairfax sites. The positioning and rotation of the antenna was optimized for each of the three stations to acquire the maximum displayed signal level. After adjustment with an antenna correction factor published for the antenna, these levels were recorded and used as the reference dipole signal levels against which the other antennas were compared.

At the Potomac Overlook site, five different passive antennas and six different active antennas were placed one at a time atop a non-conducting fiberglass pole and raised to a height of approximately nine feet above ground. The position and rotation of each of these antennas was individually optimized for reception of the three test stations, and the observed signal strength for each antenna's output level for each of the three stations was recorded.

These tests were repeated for the Potomac Ant-71 reference dipole antenna and the six active antennas at the Fairfax site.

Each of eleven consumer receive antennas was assumed to be designed to work with a receiver antenna input impedance of 75 ohms. To optimize the match between the antennas and the 50 ohm input impedance of the Potomac FIM-71 field strength meter, a minimum-loss impedance matching attenuator pad with a documented attenuation of 5.7 decibels was inserted between the these antennas and the meter. Compensation for the pad in measurements taken with the FIM-71 was accomplished by adding a 5.7 decibel adjustment to the meter readings for these antennas.

The six active antennas require 12 volts DC to power their internal electronics. This is normally supplied in the home by a small wall plug power supply. Use of such adapters in the out-of-doors is impractical, and a nominal 12 volt lead-acid utility vehicle battery and appropriate adapter cables were used to power these units. Five of the six tested active antennas offer a gain adjustment control on the antenna's housing. These five antennas were measured three times each at the two test locations, once with the gain control rotated to its maximum gain point, a second time with the gain control set at a point in the middle of its rotation, and third time with the gain control rotated to its minimum gain position. One remaining active antenna, designed primarily for outdoor use, did not offer any facility for gain adjustment.

The receive signal levels measured for each of the antennas at each test condition at both test sites are documented in tables included in Appendix E. The receive signal levels measured for each test are compared to the associated levels received via the Ant-71 reference dipole antenna, thus establishing each antenna's gain or loss relative to the reference dipole antenna. These figures are also included in the tables in Appendix F.

To establish a reference view of the FM band as received at the Potomac Overlook site, an Anritsu MS2721A RF spectrum analyzer was used to observe and record the entire FM broadcast band (88 MHz to 108 MHz) at a nominal resolution bandwidth of 30 KHz. This was accomplished using one of the passive consumer receive antennas mounted atop the nine foot mast. For this measurement, the antenna's position and rotation was optimized for reception of the station operating at 88.5 MHz. The displayed signal spectrum is shown in Appendix E Figure 1.

At both the Potomac Overlook and Fairfax sites, the Anritsu MS2721A spectrum analyzer was used to document the FM broadcast band spectrum for each of the six active receive antennas in all tested gain configurations, in each case with the antenna position and rotation optimized for reception of the station operating at 88.5 MHz. The captured spectrum displays are included in Appendix E figures 2 through 33.

SELECTION OF TESTED ANTENNAS

The antennas selected for the test are described and illustrated in Appendix D. An attempt was made to evaluate a relatively wide cross section of available passive and active indoor antennas. Two of the tested antennas were supplied as ‘standard equipment’ with commercially-available HD Radio receivers. The remaining antennas were purchased as aftermarket accessories.

Aftermarket antennas were selected following informal research conducted by NPR Labs staff members at the 2005, 2007 and 2008 Las Vegas Consumer Electronics Shows, and through various online and print sources. Several of the antennas selected were the subject both favorable and unfavorable comments by public radio station personnel on various online newsgroups and email lists. While the six active antennas represent only two manufacturers, the marketplace dominance of both—one as the sole active radio antenna offering of a nationwide retailer and the other as a manufacturer whose products are regarded as nearly synonymous with the term ‘active antenna’—justifies their selection.

CONCLUSIONS

Our findings regarding the performance of passive antennas are:

- Received signal levels between -6.9 and -37.4 dB of reference dipole; this is a very wide range in antenna efficiency, however, the folded dipole and “T” type antennas perform the best and are the largest physically; the short wire antennas, and their short telescopic whip relatives, performed the worst, but are the most convenient to use and smallest in size.
- No tendency to overload; no noise or intermodulation contribution; signal strength is usually less of a requirement than low noise and distortion, thus, passive antennas can be sized to the receive application without concern for overload (although the receiver’s own susceptibility to strong-signal overload should be considered.
- No power requirement, minimal maintenance and less costly than active antennas.

Our comments regarding performance of active antennas are:

- Prone to overload in urban and suburban environments; as shown in Appendix E, the active consumer-grade antennas may generate more intermodulation products than their gain provides, resulting in reduced receive performance. For good quieting in FM stereo, a carrier to noise ratio of at least 35 dB is required, and 45 dB is preferred. The HD Radio system requires a carrier to noise ratio of just 3 dB, but operates 20 dB below the FM host. The digital system also requires a margin above threshold for reliable reception, on the order of an additional 3-6 dB, resulting a requirement of 26-29 dB relative to the host carrier level. In a review of the antenna carrier-to-noise ratios in Appendix E it is apparent that the active antennas were incapable of delivering an adequate C/N+I in a number of cases, even though the antenna was located outdoors and only 20 miles from the reference stations. This is not adequate performance for antennas costing $30-$120.

- Poor (inadequate) gain; none of the active antennas equaled the best passive antennas in efficiency.

Our comments on the relative differences between the antennas tested:

- Active antennas have no apparent gain advantage over passive antennas.
- Active antennas are often a poor choice in urbanized and some suburban areas where high field strengths from FM and TV stations exist.
- Active antennas may be visually less obtrusive than passive antennas in domestic environments; notwithstanding their lower performance, consumers will gravitate to small, attractive active antenna designs, unaware of that they may be weakening their reception quality.

Our recommendations and suggestions regarding potential future work are:

- The public should use passive antennas, rather than active antennas, wherever possible for both cost and performance reasons.
- Laboratory tests of active antenna performance at low and elevated RF levels should be developed, to objectively quantify noise and overload performance.
- Field tests of passive and active antennas at very weak-signal locations should be performed, in particular for consumers living in fringe signal areas.
- Evaluation of commercially-available RF pre-amplifiers (for use with passive antennas) should be conducted to determine if cost-effective performance improvements are possible.
- Development of a prototype low-cost, low-noise overload-resistant active antenna, especially aimed at the HD Radio market, should be conducted.

Appendix A

IBOC Field Service Bulletin No. 02.20060216

Issued: February 16, 2006

Subject: Indoor FM HD Radio Antenna Performance

Equipment: Boston Acoustic Recepter Table Radios

Type: Anomaly

Symptom: HD Radio reception inside homes and office buildings with the new Boston Acoustics Recepter® table model radios has been disappointing for some listeners. In some cases, analog reception of hybrid stations has been adequate, but the HD Radio reception has dropped in and out, or has been non-existent. NPR Labs' measurement of this model shows very good sensitivity at the antenna input, which suggests that the supplied 18-inch wire antenna is a major fault. A better indoor FM antenna is needed to improve HD Radio reception.

Recommendations: NPR Labs obtained the following samples of active (amplified) and passive FM receive antennas for evaluation with HD Radio signals:

- Folded dipole
- Compact amplified FM-only antenna
- Compact amplified FM/AM antenna
- Rabbit-ear FM antenna

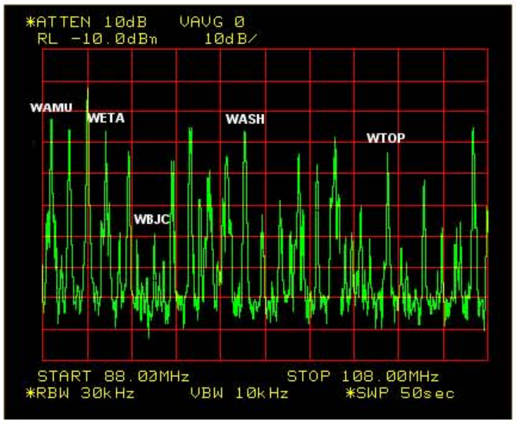
Testing is underway and a full report will be available later this year. However, the need for improved HD Radio reception indoors prompts NPR Labs to release this bulletin to help guide stations and consumers in choosing antennas that are effective in improving reception.

Preliminary testing shows a clear advantage to passive antennas, such as folded dipole and rabbit-ear types, over low-cost active antennas. The figures below show an example of the performance difference between a 75-ohm folded dipole antenna and an active FM-only antenna. These figures show the spectrum measured from 88 to 108 MHz at the NPR headquarters building in downtown Washington DC. The antennas were placed on a large empty cardboard (non-conductive) box approximately 5 feet from a north-facing 5th floor window. The spectrum plots are marked with five sample stations:

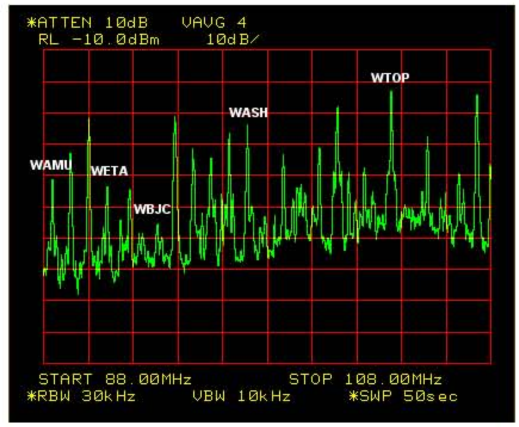
WAMU	88.5 MHz	Washington DC
WETA	90.9 MHz	Washington DC (Arlington VA transmitter)
WBJC	91.5 MHz	Baltimore MD
WASH	97.1 MHz	Washington DC

WTOP 103.5 MHz Washington DC.

The spectrum of the folded dipole shows most FM station signals ranging between -30 dBm and -50 dBm (measured with a 50-ohm spectrum analyzer input). WBJC, a Baltimore station, is shown at approximately -69 dBm. The noise floor, which is a combination of analyzer internal noise and low-level FM signals is below -90 dBm.



Folded Dipole Antenna



Active FM-Only Antenna

The gain control of the active FM-only antenna was adjusted so that the level of FM signals near the middle of the band were approximately equal to the levels measured with the folded dipole; this occurred at a rotation about 1/3 clockwise from minimum. It is apparent that gain of the antenna unit is not flat across the band; the Reserved Band (88-92 MHz) stations are at least 10 dB lower with the active antenna. The WTOP signal is approximately 20 dB higher than it was with the folded dipole. However, this signal increase is accompanied by a noise floor increase of nearly 30 dB so the net signal-to-noise ratio is decreased by approximately 10 dB. The signal-to-noise ratio for the Reserved Band stations is even worse (note that weak WBJC is almost lost in the noise). This performance was typical of other amplified antennas tested that sell for under $70.

The source of noise in amplified FM antennas is likely to be 3rd order and 5th order intermodulation products generated by the internal amplifier. Adjustment of the gain control lower will reduce the IM product levels, but also reduces the signal levels below that of the sample dipole antenna.

Suggestions of passive antennas that were found to perform well are:

- C. Crane “FM Reflect Antenna”, $24.95 (www.shop.npr.org)
- Radio Shack “Budget TV Antenna Model 15-1874”, $9.99 (www.radioshack.com)

Radio Shack Budget TV Antenna Model

CCrane FM Reflect Antenna

NPR Labs will provide updates to this field service bulletin as field information warrants.

Please contact mstarling@npr.org for further information concerning this NPR Labs FSB. Refer to Field Service Bulletin No. 02

Appendix B1

FIM-71 VHF Field Strength Meter

Key Features

Direct Reading - Volts or dB

45 MHz to 225 MHz,
Continuous Tuning

Peak or Averaging Detector

Wide or Narrow IF Bandwidth

20 dB or 60 dB Meter Bandwidth

AM or FM Demodulator

Calibrated Dipole Antenna,
Case Mount or Removable

140 dB Measurement Range
(1 µV to 10 V)

4 ½-inch , Mirrored Scale
Taut-Band Meter

Front Panel Speaker

Rugged, Portable

Nylon Carrying Case

Description

The Model FIM-71 is a portable, laboratory quality Field Strength Meter designed for rigorous field applications. Combining a calibrated half-wave dipole antenna and a highly accurate tuned voltmeter with a range of 140 dB, the FIM-71 is suitable for practically all types of RF emission measurements in the 45 MHz to 225 MHz spectrum. The operator can switch select wide or narrow bandwidth, peak or average value of TV or pulse modulated signals, AM or FM demodulation, and a meter dynamic range of either 20 dB or 60 dB. A dc analog output voltage, proportional to the meter indication, is provided for driving a chart recorder. A leveled output from the calibrating oscillator is available for measuring cable insertion loss, filter response, amplifier gain, and other signal ratio measurements. The 4 ½-inch, taut band, mirrored scale meter is calibrated in volts and dB for precise measurements in field or laboratory environments.

The tuned voltmeter is a single conversion, super-hetrodyne receiver with carefully tailored sensitivity, gain, and linearity characteristics. The RF input is double tuned and designed for minimum VSWR and maximum out-of-band signal rejection. Uniform gain, independent of IF bandwidth, is provided by temperature compensated RF & IF amplifiers utilizing a combination of MOSFET, J-FET, bipolar, and monolithic integrated circuit devices. The linear detector is followed by an algorithmic shaping circuit which drives the meter in the LIN (20 dB) mode. In the LOG mode the meter indication (in dB) varies linearly over a one-thousand-to- one range of input levels.

Options: AC power adapter, rechargeable battery kit, unipod, spare antenna elements and balun, and headset.

Potomac Instruments, inc.
932 Philadelphia Ave./ Silver Spring, MD 20910-4912 / Voice: 1 301.589.2662 / Fax: 1 301.589.2665 / web: www.pi-usa.com

FIM-71 Specifications

FREQUENCY RANGE	45 MHz - 225 MHz; continuous.
RF INPUT IMPEDANCE/VSWR	50 ohms VSWR 1.2:1, 100µV full scale and greater. VSWR 1.5:1, 10µV full scale.
VOLTAGE MEASUREMENT	1µV to 10 V rms in seven switch selected ranges.
METERING	4-½ inch meter, mirror backed scale, taut band meter
INDICATION MODES	LINear and LOGarithmic, switch selected.
METER SCALES	LIN mode: 1-10 (logarithmic scale) and 0-20 dB (linear scale). LOG mode: -20 to +40 dB (60 dB range, linear scale) Battery voltage/External supply voltage scale.
METERING DETECTORS	Average responding and peak responding (for television sync pulse), switch selected.
RECEIVER BANDWIDTHS	AM/FM: 190 kHz at -3 dB, and TV: 450 kHz at -3 dB, front panel switch selected
ABSOLUTE ACCURACY	Voltage: ±1.5 dB (LIN), ±2.0 dB (Log); for voltage >1.5µV (AM/FM) or >3 µV (TV) Field Strength: ±3.0 dB (LIN), ±3.5 dB (LOG) for field strengths >1.8 µV/M (AM/FM) or >3.7 µV/M (TV) at 45 MHz; >9.1 V/M (AM/FM) or 18.1µV/M (TV) at 225 MHz; using the supplied antenna.

Note: These figures apply when using the Average Detector; for the Peak Detector, noise correction factors (supplied) are required below 10 mV

RELATIVE ACCURACY	±1 dB at one frequency, for voltage or field strength, LIN mode, for voltages >10 µV, with noise correction factors.
HARMONIC MEASUREMENT	Measures second harmonic field strength of 87.5 Mhz - 108 MHz signals to -80 dB for fundamental voltage less than 100mV
CALIBRATING OSCILLATOR	Output switched to receiver for internal calibration, to external output (BNC connector) or OFF. Tracks receiver frequency when connected to receiver.
Output Level and Accuracy	100 mV ±0.3 dB across 50.0 ; (45 MHz to 225 MHz.)
FREQUENCY DIAL	Six-turn spiral, continuous tuning, movable cursor.
Accuracy	± 0.5% of indicated frequency without cursor correction. ±200 kHz typical, 87.5 MHz - 108 MHz, after setting cursor on known signal
RCVR SPURIOUS RESPONSE	Image Rejection, 55 dB typical; IF Rejection, 100 dB typical.
LOCAL OSC RADIATION	45 MHz, 2 µV; 225 MHz, 35 µV; typical values across 50 ohm load at RF input connector
DEMODULATORS	AM and FM; switch selected, phone jack (0.25") output connector
Video Frequency Response	50 Hz - 100 kHz, 3 dB max. variation.
Output Level	4.5 V p-p max. across 75 ohm load, front panel adjustable
AUDIO MONITORING	Internal loudspeaker; headphones plug into demodulator output jack (disconnecting speaker); AM or FM selected by DEMOD switch: level control with disabling switch
RECORD OUTPUT	Two-circuit phone jack (.25") output.
Tip Contact	DC analog of meter indication -0.8 V to - 8 V (open circuit), 2000 ohm source resistance.
Ring Contact	DC output of FM discriminator, @ -5 V ±3 V, 10,000 ohm source resistance. (Single circuit phone plug provides tip contact output only.)
POWER SUPPLY	
Internal Batteries	1.5 volt size “D” batteries, ten required.
Battery Life	1500 readings or 18 hours continuous operation using Eveready No. 950 batteries (or equivalent) at 70°F.
External Supply	11.5 volts to 19.0 volts DC, positive ground, 120 mA, Switchcraft No. 760 Connector (or equivalent).
TEMPERATURE RANGE	+15°F to +105 °F (-10°C to +40°C).
DIMENSIONS, INCHES (CM)	Without Antenna: 9.5 (24) high, 12.25 (31) wide, 7.25 (18.4) deep With Antenna attached and retracted, 9.9 (25) high, 13.5 (34.3) wide, 7.25 (18.4) deep
WEIGHT, POUNDS (KG)	20 (9.1) with batteries, antenna, cover, cables and softcase

Note: Values without limits are typical only. Field strength data are with ANT-71 Antenna

Antenna Ant-71

Type:	Tunable half-wave dipole with continuously adjustable telescoping elements.
Frequency Range:	45 Mhz to 225 MHz.
Calibration:	Antenna Factor data supplied based on NIST calibration; overall error including NIST calibration uncertainty, ±1.5 dB max.
Load Impedance:	50 ohms
Mounting:	Mounts on case for hand-held measurements at an antenna height of approx. 7ft.; has 1/4-20 threaded hole for mounting to other masts.

Specifications subject to change without notice.

PI

Potomac Instruments, inc.

932 Philadelphia Ave./ Silver Spring, MD 20910-4912 / Voice: 1 301.589.2662 / Fax: 1 301.589.2665 / web: www.pi-usa.com

Appendix B2

Spectrum Master™

MS2721A

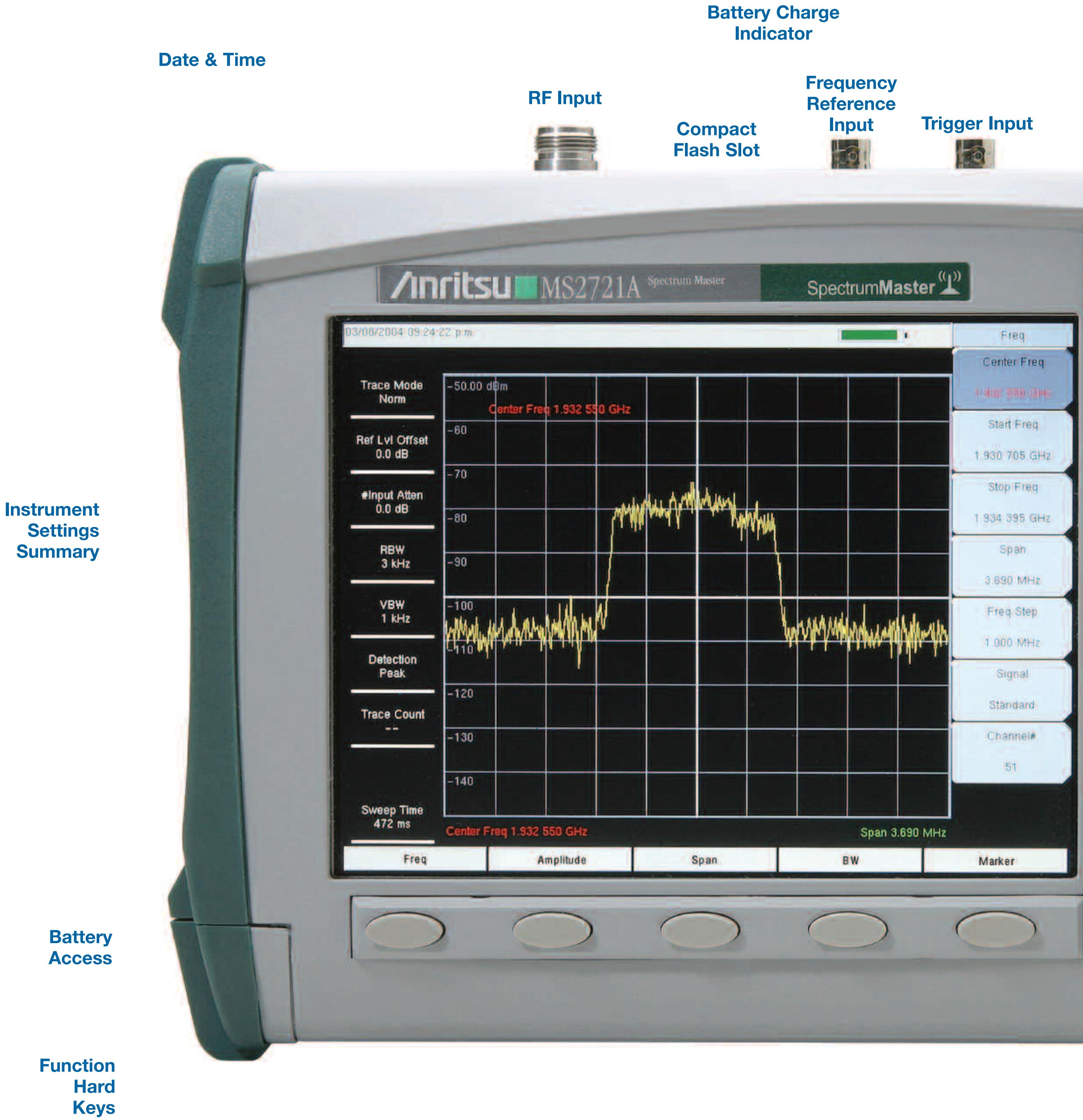
High Performance Handheld Spectrum Analyzer

SpectrumMaster

- 100 kHz to 7.1 GHz
- +43 dBm maximum safe input power
- Ethernet and USB 2.0 remote control
- –100 dBc/Hz @ 10 kHz offset at 7.1 GHz

High Performance Handheld Spectrum Analyzer

The Anritsu MS2721A is the most advanced ultra-portable spectrum analyzer on the market, featuring unparalleled performance and size at a modest price.

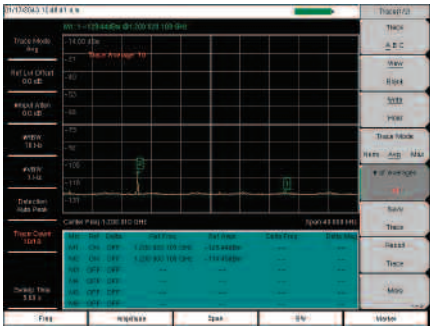


≤–153 dBm Displayed Average Noise Level Typical @ 1 GHz

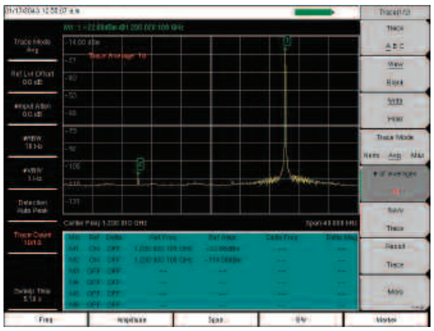
Unprecedented in handheld battery powered spectrum analyzers, the sensitivity of the MS2721A delivers the ability to measure very low level signals. Coupled with a wide range of resolution bandwidth choices, you can configure the Spectrum Master to meet your most challenging measurement needs.

As the spectrum becomes more and more congested, the ability to measure low level signals becomes more and more important not only for interference detection but also for wireless system planning.

Field Use



Measuring a Small Signal



Wide Dynamic Range — Measuring a small signal in the presence of a very large signal

Operating convenience is of paramount importance when equipment is used in the field.

The input attenuation value can be tied to the reference level, reducing the number of parameters a field technician may have to set. The RBW/VBW and the span/RBW ratios can be set to values that are best for the measurements being made, further easing the technician's burden and reducing the chances of errors.

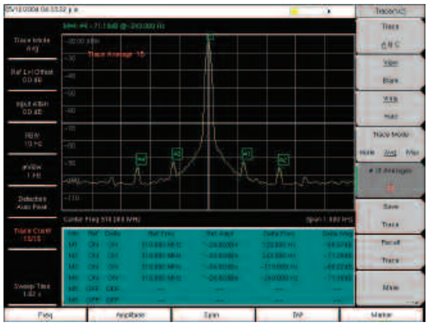
Thousands of traces with names up to 15 characters long may be saved in the 64 MB non-volatile compact flash memory. These traces can later be copied into a PC using the built-in USB 2.0 connector or the 10/100 Mbit Ethernet connection.

Commonly needed measurements are built in. These include field strength, occupied bandwidth, channel power, adjacent channel power ratio, AM/FM/SSB demodulation and carrier to interference (C/I) ratio measurements.

The MS2721A Spectrum Master has a very wide dynamic range, allowing measurement of very small signals in the presence of much larger signals. These pictures show a measurement of a –114 dBm signal with and without the presence of a –22 dBm signal only 20 kHz away.

Measurement Area	Wide RBW & VBW Range	AM/FM Demod	Channel Power	ACPR	OBW	Field Strength	C/I
Cellular Measurements			yes	yes	yes	yes	yes
WiFi Measurements			yes		yes	yes	yes
Spectrum Monitoring	yes	yes					
Interference Detection	yes	yes				yes	

Lab Use



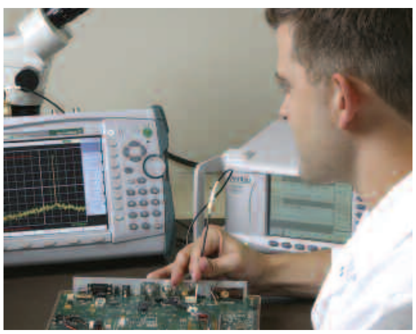
Powerline related sidebands on a synthesized signal generator

Measurement flexibility is important for lab use. Resolution bandwidth and video bandwidth can be independently set to meet a user's measurement needs. In addition the input attenuator value can be set by the user and the preamplifier can be turned on or off as needed.

For maximum flexibility, sweep triggering can be set to free run, or to do a single sweep. In zero span, the sweep can be set to trigger when a signal meets or exceeds a certain power level or it can be externally triggered.

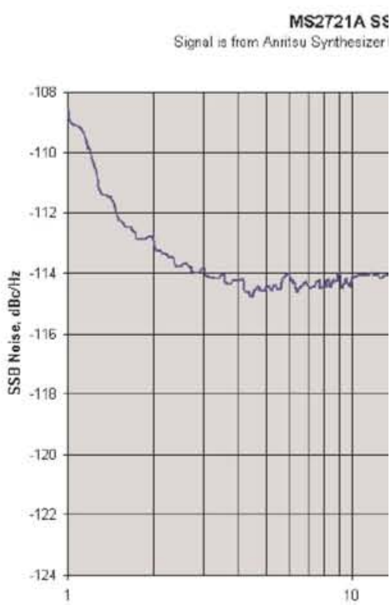
The span can be set anywhere from 10 Hz to 7.1 GHz in addition to zero span.

Using battery-powered equipment to measure powerline related sidebands on a signal source removes any question as to the source of the sidebands.



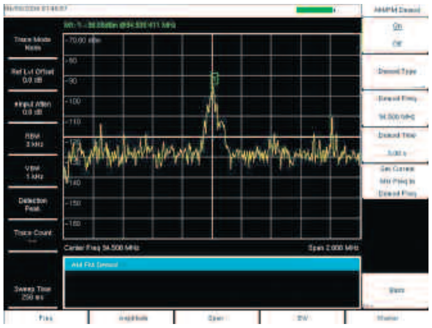
Continuous frequency coverage from 100 kHz to 7.1 GHz gives the wireless professional the performance needed for the most demanding measurements.

Whether your need is for spectrum monitoring, WiFi and WiFi5 installation and testing, RF and microwave signal measurements or cellular signal measurements, the MS2721A Spectrum Master gives you the tools you need to make the job easier and more productive. The built-in AM/FM/SSB demodulator simplifies the job of identifying interfering signals.

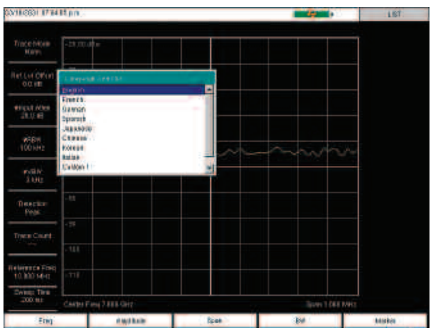


Typical Phase Noise Performance

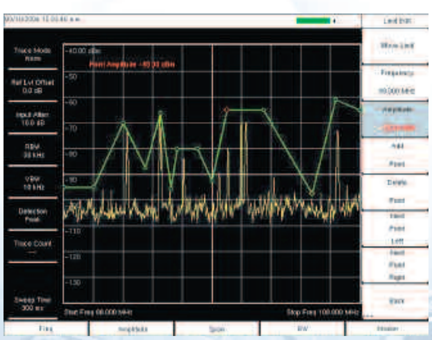
Features



AM, FM and SSB Demodulation



Multiple Language Support



Segmented Limit Lines

Light Weight

Weighing about six pounds fully loaded, including a Li-Ion battery, this fully functional handheld spectrum analyzer is light enough to take anywhere, including up a tower.

AM/FM Demodulation

A built-in demodulator for AM, narrowband FM, wideband FM and single sideband (selectable USB and LSB) allows a technician to easily identify interfering signals. The demodulated audio can be heard either through the built-in speaker or through a standard headset. A demodulation marker is provided for easy tuning.

Remote Tools

Imagine sitting at your desk while controlling an MS2721A that is miles away, seeing the screen display and operating with an interface that looks exactly like the instrument itself. That is what Remote Tools lets you do.

Local Language Support

The MS2721A features eight languages English, Spanish, German, French, Japanese, Chinese, Italian and Korean, two custom user-defined languages can be uploaded into the instrument using Master Software Tools, supplied with the instrument.

Fast Sweep Speed

The MS2721A can do a full span sweep in ≤900 milliseconds, and sweep speed in zero span can be set from 50 microseconds up to 4294 seconds. This is faster and more flexible than any portable spectrum analyzer on the market today, simplifying the capture of intermittent interference signals.

+43 dBm Maximum Safe Input Level

Because the MS2721A can survive an input signal of +43 dBm (20 watts) without damage, you can rest assured that the MS2721A can survive in even the toughest RF environments.

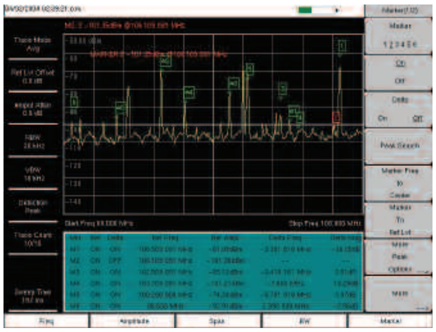
Spectrum Monitoring

A critical function of any spectrum analyzer is the ability to accurately view a portion of the RF and microwave spectrum. The MS2721A performs this function admirably thanks to the wide frequency range and excellent dynamic range. A built-in 64 MB compact flash memory module allows thousands of traces to be stored. The external compact flash connector allows additional compact flash memory to expand the trace storage without limit.

Limit Lines

The MS2721A includes two types of limit lines, lower limit lines and upper limit lines. Limit lines may be used either for visual reference or for pass/fail criteria by implementing limit alarms. Limit alarm failures are reported if a signal is above the upper limit line or below the lower limit line. Each limit line may consist of up to 40 segments.

Features



Multiple Markers plus Multiple Delta Markers

Multiple Markers

Display up to six markers on screen, each with delta marker capability. In addition, you may select a marker table that simultaneously shows the status of all markers. In the table you can see the frequency and amplitude measurement value for all markers, along with delta frequency and delta amplitude. Each marker can have not only a measurement reference frequency but also a delta frequency and delta amplitude, effectively giving you up to twelve markers if you need them!

Noise Markers

The capability to measure noise level in terms of dBm/Hz or dBμV/Hz is a standard feature of the MS2721A.

Frequency Counter Markers

The MS2721A Spectrum Master has frequency counter markers with resolution to 1 Hz. Tie this capability to an external precision time base to get complementary accuracy.

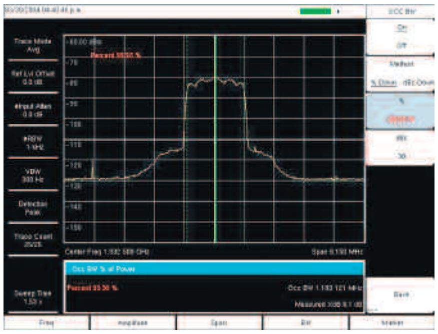
Functions

Multiple Marker	Display up to six markers on screen, each marker includes a delta marker.
Marker Table	Display a table of up to six marker frequency and amplitude values plus delta marker frequency offset and amplitude.
Upper/Lower Limit Fixed and Segmented	Each upper and lower limit can be made up of between one and 40 segments.

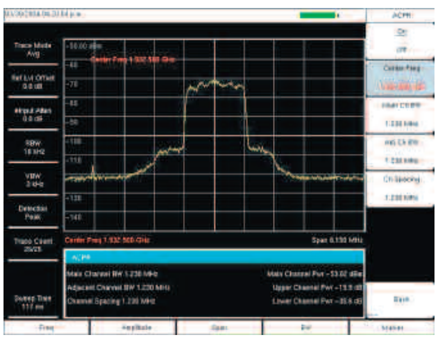
Smart Measurements

Occupied Bandwidth	Measures 99.99% to 1% power bandwidth of a spectrum.
Channel Power	Measures the total power in a specified bandwidth.
C/I	Measures the carrier to interference ratio in a specified bandwidth.
ACPR	Measures power levels in the channels immediately above and below the center channel.
Field Strength	Uses antenna calibration tables to measure dBm/meter or dBmV/meter.
AM/FM/SSB Demodulation	Allows the user to listen to interfering signals. De-emphasis is included for narrow-band FM and wideband FM. Upper Sideband and Lower Sideband demodulation includes a BFO that can be tuned ±10 kHz from the center frequency.

Measurements



Occupied Bandwidth



Adjacent Channel Power Ratio

Smart Measurements

The MS2721A has dedicated routines for one-button measurements of field strength, channel power, occupied bandwidth, Adjacent Channel Power Ratio (ACPR) and C/I. These are increasingly critical measurements for today's wireless communication systems. The simple interface for these complex measurements significantly reduces test time and increases analyzer usability.

Fast Sweep Speed

The MS2721A can do a full span sweep in <900 milliseconds, and sweep speed in zero span can be set from 50 microseconds to 4294 seconds. This is faster and more flexible than any portable spectrum analyzer on the market today, simplifying the capture of intermittent interference signals.

Carrier to Interference Measurement

As more 802.11 access points are installed, there is an increasing level of interference in the 2.4 GHz and 5.8 GHz bands occupied by this service and other devices such as cordless telephones. This measurement capability makes it simple for an access point installer to determine if the level of interference is sufficient to cause difficulty for users in the intended service area, and can show the need to change to another access channel. The wide frequency coverage of the MS2721A makes this the only spectrum analyzer you need to install and maintain 802.11a, 802.11b and 802.11g wireless networks.

Occupied Bandwidth

This measurement determines the amount of spectrum used by a modulated signal. You can choose between two different methods of determining bandwidth: the percent of power method or the "x" dB down method, where "x" can be from 3 dB to 100 dB down the skirts of the signal.

Adjacent Channel Power Ratio

A common transmitter measurement is that of adjacent channel leakage power. This is the ratio of the amount of leakage power in an adjacent channel to the total transmitted power in the main channel, and is used to replace the traditional two-tone intermodulation distortion (IMD) test for system non-linear behavior.

The result of an ACPR measurement can be expressed either as a power ratio or a power density. In order to calculate the upper and lower adjacent channel values, the MS2721A allows the adjustment of four parameters to meet specific measurement needs: main channel center frequency, measurement channel bandwidth, adjacent channel bandwidth and channel spacing. When an air interface standard is specified in the MS2721A, all these values are automatically set to the normal values for that standard.

Frequency

Frequency Range	100 kHz to 7.1 GHz
Tuning Resolution	1 Hz
Frequency Reference	Aging ±1 ppm/year Accuracy ±1 ppm (25°C ±25°C) + long term drift
Frequency Span	10 Hz to 7.1 GHz plus 0 Hz (zero span)
Span Accuracy	Accuracy ±1 ppm (25°C ±25°C) + long term drift
Sweep Time	minimum 100 ms, 50 μs in zero span
Sweep Time Accuracy	±2% in zero span
Sweep Trigger	Free run, Single, Video, External
Resolution Bandwidth	(–3 dB width) 10 Hz to 3 MHz in 1-3 sequence ±10%, 8 MHz demodulation bandwidth
Video Bandwidth	(–3 dB) 1 Hz to 3 MHz in 1-3 sequence
SSB Phase Noise	–100 dBc/Hz max at 10, 20 and 30 kHz offset from carrier –102 dBc/Hz max at 100 kHz offset from carrier

General

Maximum Continuous Input	≥10 dB attenuation, +30 dBm
Input Damage Level	≥10 dB attenuation, >+43 dBm, ±50 Vdc <10 dB attenuation , >+23 dBm, ±50 Vdc Input protection relay opens at >30 dBm with ≥10 dB input attenuation and at approximately 10 to 23 dBm with <10 dB attenuation
RF Input VSWR	2.0:1 maximum, 1.5:1 typical (≥10 dB attenuation)
Reference Level	Adjustable over amplitude range
ESD Damage Level	>10 kV ≥10 dB attenuation

Amplitude

Measurement Range	DANL to +30 dBm
Absolute amplitude accuracy **Power levels ≥–50 dBm, ≥35 dB input attenuation, preamp off**	100 kHz to ≤10 MHz ±1.5 dB >10 MHz to 4 GHz ±1.25 dB >4 GHz to 7.1 GHz ±1.75 dB
Second Harmonic Distortion **(0 dB input attenuation, –30 dBm input)**	–50 dBc, 0.05 to 0.75 GHz –40 dBc, >0.75 to 1.05 GHz –50 dBc, >1.05 to 1.4 GHz –70 dBc, >1.4 to 2 GHz –80 dBc, >2 GHz

Amplitude

Third Order Intercept (TOI) (preamplifier off)
–20 dBm tones 100 kHz apart
–20 dBm reference level
0 dB attenuation

Frequency	Typical
50 MHz to 300 MHz	>8 dBm
>300 MHz to 2.2 GHz	>10 dBm
>2.2 GHz to 2.8 GHz	>15 dBm
>2.8 GHz to 4.0 GHz	>10 dBm
>4.0 GHz to 7.1 MHz	>13 dBm

Displayed Average Noise Level
DANL in 10 Hz RBW, 0 dB attentuation
reference level –50 dBm

Frequency	Preamp On	
	Typical	Max
10 MHz to 1 GHz	–153 dBm	–151 dBm
>1 GHz to 2.2 GHz	–150 dBm	–149 dBm
>2.2 GHz to 2.8 GHz	–146 dBm	–143 dBm
>2.8 GHz to 4.0 GHz	–150 dBm	–149 dBm
>4.0 GHz to 7.1 GHz	–148 dBm	–144 dBm

Noise Figure (Derived from DANL measurement)
0 dB attenuation, reference level
–50 dBm, 23°C, preamp on

Frequency	Typical
10 MHz to 1.0 GHz	11 dB
>1 GHz to 2.2 GHz	14 dB
>2.2 GHz to 2.8 GHz	18 dB
>2.8 GHz to 4.0 GHz	14 dB
>4.0 GHz to 7.1 GHz	16 dB

Display Range	1 to 15 dB/div in 1 dB steps. Ten divisions displayed.
Amplitude Units	Log Scale modes: dBm, dBV, dBmv, dBµV Linear Scale modes: nV, µV, mV, V, kV, nW, µW, mW, W, kW
Attenuator Range	0 to 65 dB
Attenuator Resolution	5 dB steps
Input-Related Spurious	–60 dBc max*, (<–70 dBc typical), –30 dBm input, 0 dB RF attenuation
*Exceptions:	
Input Frequency	Spur Level
1674 MHz	–46 dBc max (–56 dBc typical), 0 to 2800 MHz
>1674 to 1774 MHz	–50 dBc max (–60 dBc typical) at (F_{input} – 1674 MHz)

Residual Spurious, Preamp Off
(RF input terminated, 0 dB RF attenuation)

–90 dBm max**, 100 kHz to <3200 MHz
–84 dBm max**, 3200 to 7100 MHz

**Exceptions:

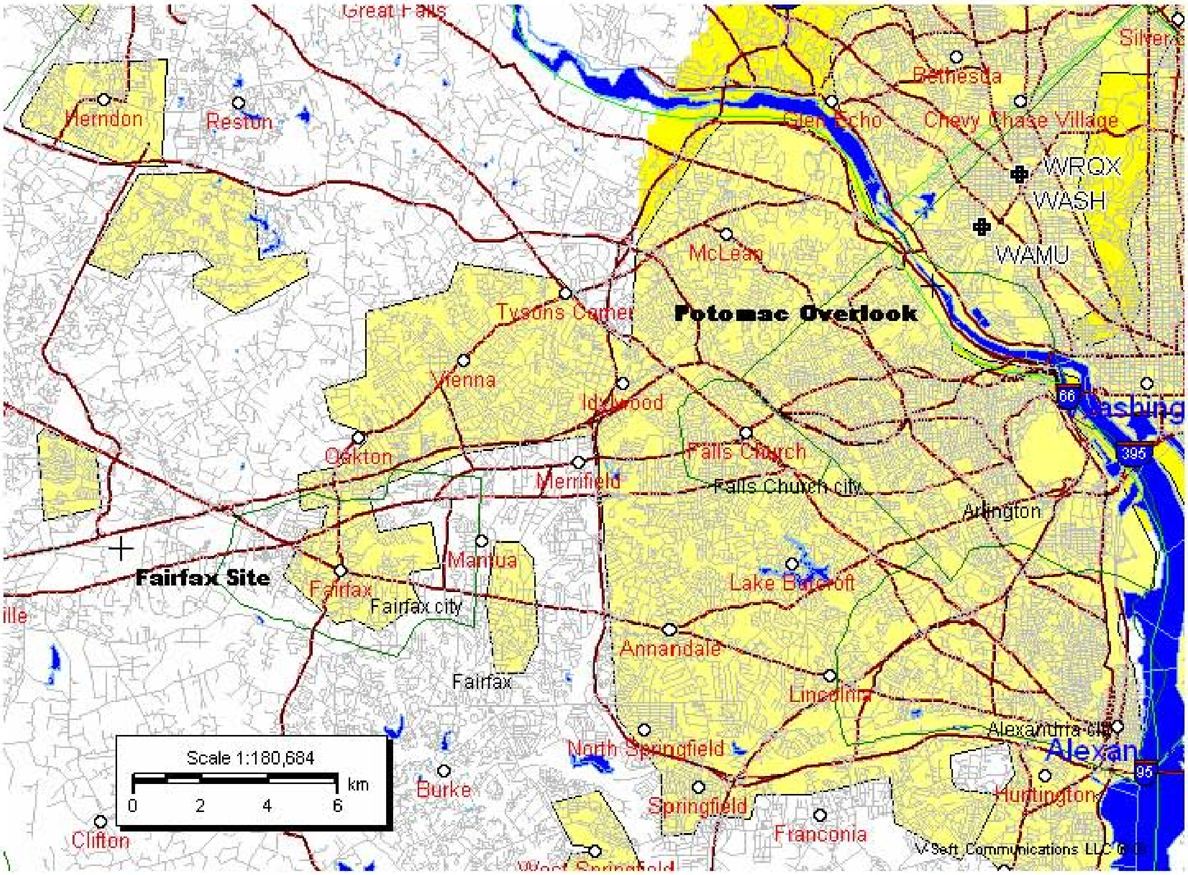
Frequency	Spur Level
250, 300 and 350 MHz	–85 dBm max
~4010 MHz	–80 dBm max (–90 dBm typical)
~5084 MHz	–70 dBm max (–83 dBm typical)
~5894 MHz	–75 dBm max (–87 dBm typical)
~7028 MHz	–80 dBm max (–92 dBm typical)

Residual Spurious, Preamp On:	–100 dBm max (RF input terminated, 0 dB RF attenuation)

APPENDIX C

Figure 1 is a map showing the location of the three reference FM stations and the two test sites.

Figure 1 Map of test sites and reference FM stations



Figures 2, 3 and 4 show the terrain profiles from the radiation center of each reference FM station to the Potomac Overlook site. The direct path ray and an ellipse depicting 60 percent of the first Fresnel zone for each ray is included. The line-of-sight path ensures that the field strengths are close to free-space values. The lack of ground reflection effects, due to the steep bank of the Potomac River basin, minizes standing waves and multipath. These factors combine to make the Potomac Overlook site an excellent test range for FM antennas.

Figure 2 Terrain Profile—WAMU to Potomac Overlook

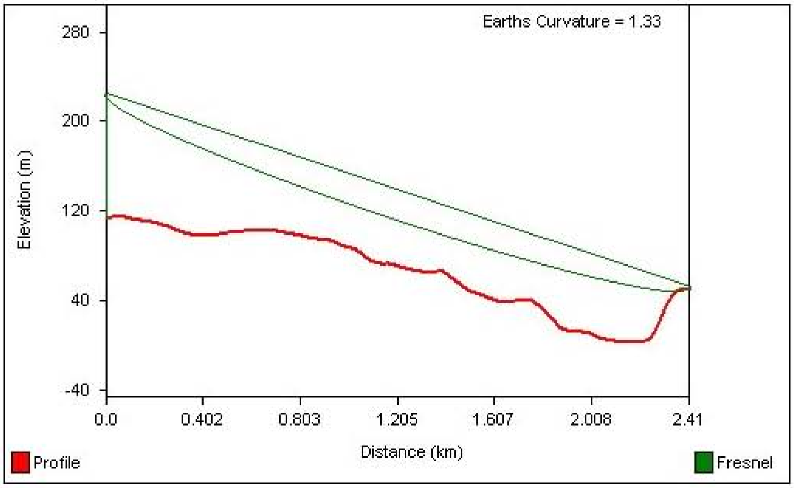


Figure 3 Terrain Profile—WASH-FM to Potomac Overlook

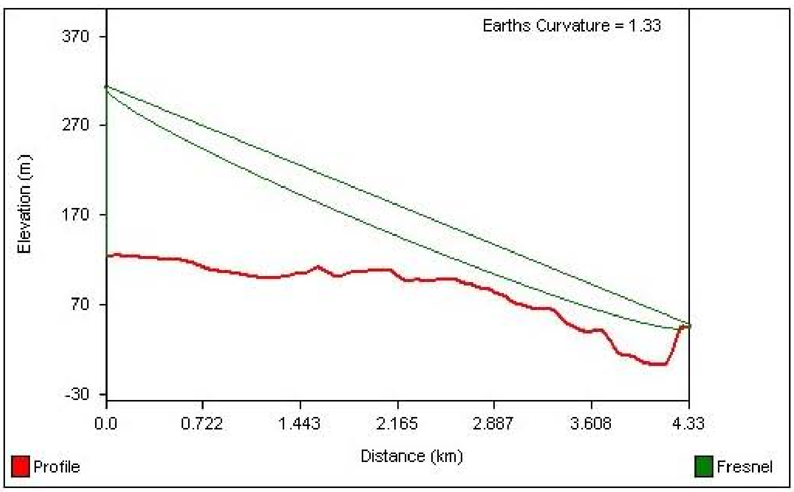
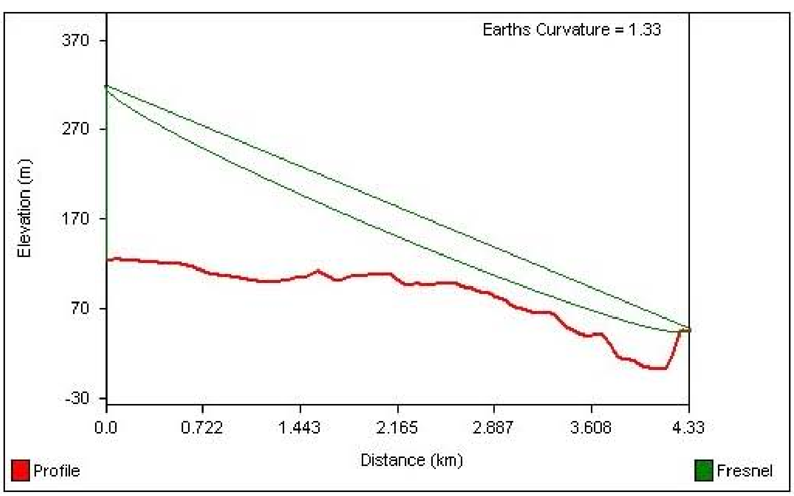


Figure 4 Terrain Profile—WRQX-FM to Potomac Site



The photo of Figure 5 shows the view looking northeast toward the FM and TV broadcast towers in Northwest Washington. The ground beyond the rock wall in the lower part of the picture immediately recedes, which avoids ground reflection effects.

Figure 5 View toward transmitters from Potomac Overview site

The view looking east at the Fairfax, Virginia, site is shown in Figure 6. This site has a grazing path to the reference FM stations, approximately 20 miles distant. The foreground of the site is elevated and tilted away from the transmitter rays, minimizing ground reflections. This site is more than 8 miles from the nearest FM transmitter, which helps minimize strong signal overload that could affect measurements of active antennas.

Figure 6 View toward transmitters from Fairfax site

Appendix D

The twelve antennas used in the Indoor Receive Antenna tests are described and pictured herein.

Passive Antennas

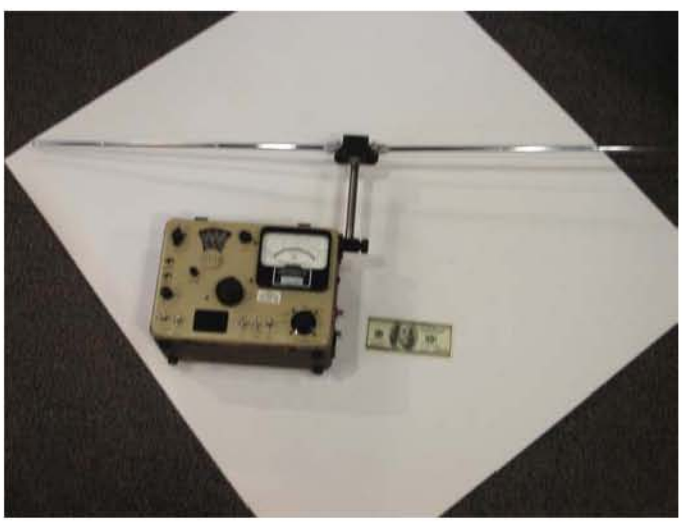
Manufacturer	Model	Description	Approx. Price
Potomac Instruments	Ant-71	NIST[1]-traceable reference antenna, tunable	$1,540
C.C. Crane	FM Reflect	dipole constructed of coaxial cable	$25
Boston Acoustics	(dipole)	nom. 75 ohms w/type F connector	bundled or $1–4
Boston Acoustics	(wire lead)	'rat tail' antenna w/type F connector	bundled
Fanfare	FM-2G	base-loaded whip (56 inches)	$99
Terk	FM+	'bookshelf' panel antenna	—

[1]*National Institute of Standards and Technology*

Potomac Instruments Ant-71 Reference Dipole Antenna

This professional antenna, used in these test, is part of the industry-standard Potomac Instruments FIM-71 FM radio field intensity meter. The simple but precision design allows the antenna to be adjusted to resonate at the frequency of interest. It includes a high-quality impedance matching transformer and is equipped with 'professional' type BNC RF connectors.

Figure 1 Potomac Instruments Ant-71 Reference Dipole (on FIM-71 Meter)



When used with the supplied adjustment and compensation charts, the antenna can be used as a 'reference' half-wave dipole, traceable to the National Institute of Standards, with an accuracy of approximately +/–1.5 dB.

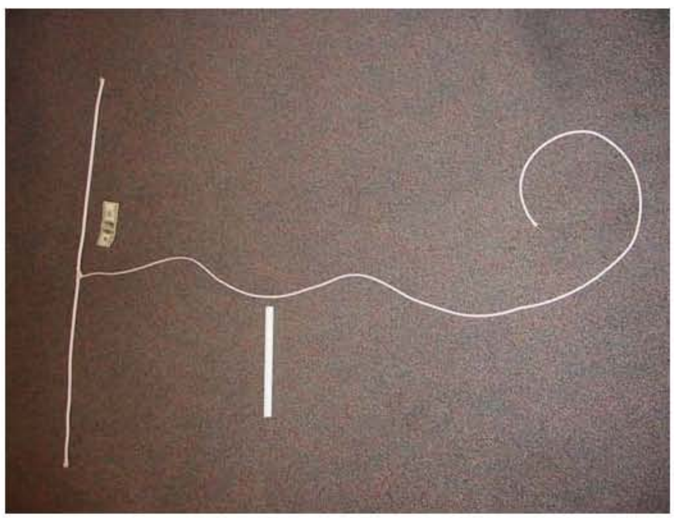
During these tests, the Potomac Instruments ANT-71 antenna was attached to the FIM-71 meter via its telescoping mast, and was elevated approximately 9 feet above ground.

C. Crane FM Reflect Dipole

This is a classic 'T' dipole antenna, nominally designed for wall mounting near a receiver. It is constructed entirely of coaxial cable, has a nominal output impedance of 75 ohms and uses a conventional threaded male F connector. The length of its dipole elements (54 inches) and performance suggest that the antenna is optimized for the middle of the FM band.

The Crane FM Reflect dipole was tested by attaching it to a narrow wooden crosspiece mounted on the fiberglass pole, and elevated approximately 9 feet above ground.

Figure 2 Crane FM Reflect Dipole Antenna

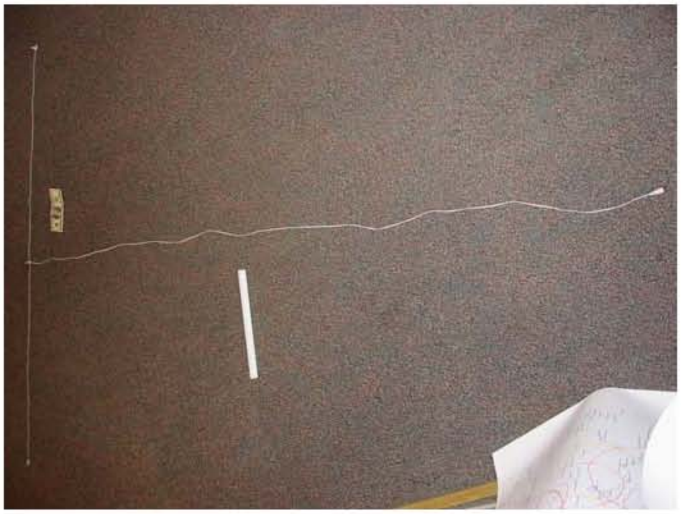


Boston Acoustics FM Dipole

This antenna is typical of those included with many models of HD Radio receivers. A 'classic' FM folded half-wave FM dipole antenna is constructed entirely of 300 ohm twin-lead antenna cable, and provides an output impedance of 300 ohms. The 'dipole' elements of this antenna are each constructed of single wire conductors, and a closely space pair of wires terminated in a push-on F connector serves as its downlead, suggesting an impedance of 75 ohms. The length (62 inches) and performance of the tested antenna suggest that it was optimized for the lower end of the FM band.

The Boston Acoustic FM Dipole was tested by attaching it to a narrow wooden crosspiece mounted on the fiberglass pole, and elevated approximately 9 feet above ground.

Figure 3 Boston Acoustics FM Dipole Antenna

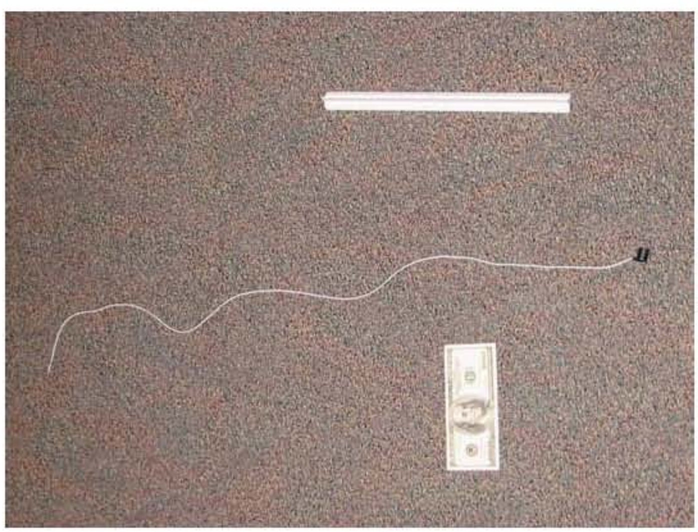


sBoston Acoustics Wire Lead Antenna

This is a simple wire lead approximately 36 inches in length, terminated in a push-on F connector. If the wire is pulled taut and straight, its performance will resemble a simple whip antenna of similar length. Since it is relatively short in length compared to the wavelength of an FM broadcast signal, it would be expected to deliver uniform performance across the FM band.

The Boston Acoustics Wire Lead Antenna was taped vertically to the non-conducting fiberglass mast and elevated approximately nine feet above ground.

Figure 4 Boston Acoustic Wire Lead Antenna

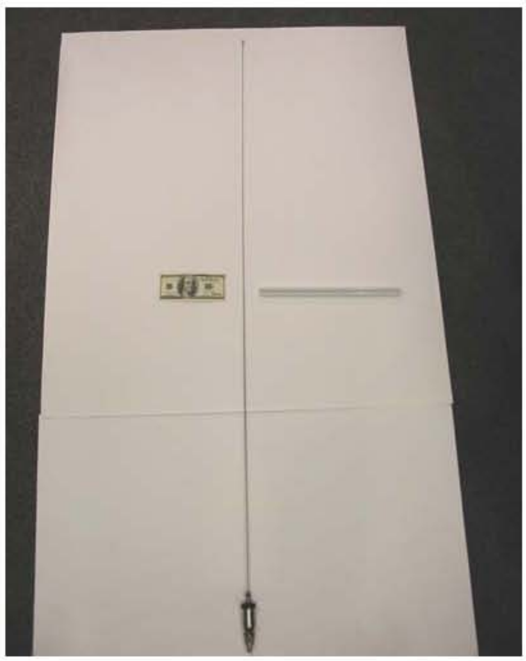


Fanfare FM-2G FM Whip Antenna

This antenna consists of a 56 inch metal whip attached to a small base, said to contain a matching transformer. It is equipped with a UHF-type output connector, and is supplied with an F-type adapter. No attempt is made to provide a ground plane or counterpoise. Nominal output impedance is 75 ohms. A version is available equipped with a 66 inch whip, which is claimed to optimize the antenna for the 'educational' (reserved channels) section of the FM band.

The Fanfare FM-2G FM Whip Antenna was tested by being attached to the top of the nine foot non-conducting fiberglass mast.

Figure 5 Fanfare FM-2G FM Vertical Whip Antenna



Terk FM+ Passive Antenna

The Terk FM+ Antenna is a passive design, consisting of a panel-shaped plastic box approximately seven inches square. Output is provided to a push-on F connector via a short, thin round cable presumed to be coaxial.

The Terk FM+ Antenna was tested by attaching it to the top of a fiberglass pole and elevating it to approximately nine feet above ground.

Figure 6 Terk FM+ Passive Antenna

Active Antennas

Manufacturer	Model	Description	Approx. Price
Radio Shack	15-1589	‘bookshelf’ amplified panel, AM/FM	$30
Terk	Edge	‘’bookshelf’ amplified panel, FM only	$25
Terk	Tower AF9330	‘tabletop’ amplified vertical, AM/FM	$25
Terk	Pi	‘bookshelf’ amplified panel/loop, AM/FM	$35
Terk	HDR-I	HD-specific bookshelf amplified panel, AM/FM	$50
Terk	HDR-O	HD-specific whip/loop outdoor/attic, AM/FM	$129

Radio Shack 15-1589 AM/FM Active Antenna

This unit consisting of a panel-shaped plastic box approximately seven inches square. It requires an external 12 VDC power source (which was supplied for the tests by a small lead-acid utility vehicle battery), and is equipped with a rotary gain control. Output is provided to a push-on F connector via a short, thin round cable presumed to be coaxial. A separate cable (untested) is available for AM.

The Radio Shack 15-1589AM/FM Active Antenna was tested by attaching it to the top a fiberglass pole and elevating it approximately nine feet above ground.

Figure 7 Radio Shack 15-1589 AM/FM Active Antenna

Terk Edge FM4000 FM Active Antenna

This unit consisting of a panel-shaped plastic box approximately seven inches wide by eight inches tall. It requires an external 12 VDC power source (which was supplied for the tests by a small lead-acid utility vehicle battery), and is equipped with a rotary gain control. Output is provided to a push-on F connector via a short, thin round cable presumed to be coaxial.

It was tested by attaching it to the top a fiberglass pole and elevating it approximately nine feet above ground.

Figure 8 Terk Edge FM4000 FM Active Antenna

Terk Tower AF9330 AM/FM Active Antenna

This unit consisting of a thin vertical plastic box approximately sixteen inches talls. It requires an external 12 VDC power source (provided by a small lead-acid utility vehicle battery), and is equipped with a rotary gain control. Output is provided to a push-on F connector via a short, thin round cable presumed to be coaxial. A separate cable (untested) is available for AM.

The Terk Tower AF9330 AM/FM Active Antenna was tested by attaching it to the top a fiberglass pole and elevating it approximately nine feet above ground.

Figure 9 Terk Tower AF9330 AM/FM Active Antenna

Terk Pi-B AM/FM Active Antenna

This unit consisting of a panel-shaped plastic box approximately six inches in diameter, surrounded by a slightly large plastic ring. It requires an external 12 VDC power source (which was supplied for the tests by a small lead-acid utility vehicle battery), and is equipped with a rotary gain control. Output is provided to a push-on F connector via a short, thin round cable presumed to be coaxial. A separate cable (untested) is available for AM.

The Terk Pi-B AM/FM Active Antenna was tested by attaching it to the top a fiberglass pole and elevating it approximately nine feet above ground.

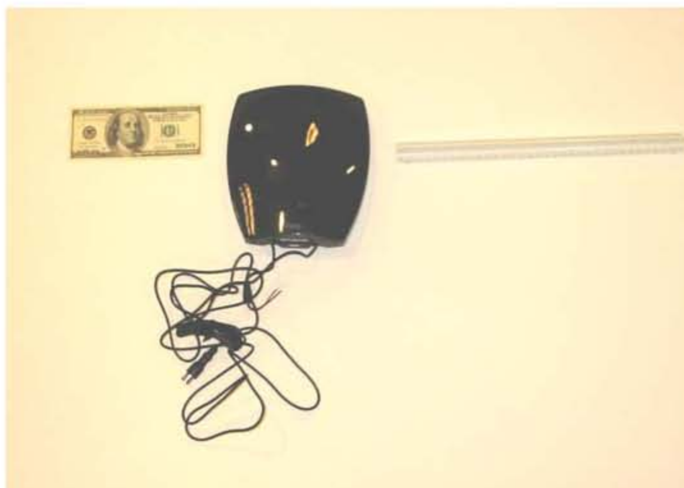
Figure 10 Terk Pi-B AM/FM Active Antenna

Terk HDR-I 'Indoor' AM/FM Active Antenna

This unit, which is marketed as supporting HD Radio reception, consisting of a panel-shaped plastic box approximately eight inches square. It requires an external 12 VDC power source (which was supplied for the tests by a small lead-acid utility vehicle battery), and is equipped with a rotary gain control. Output is provided to a push-on F connector via a short, thin round cable presumed to be coaxial. A separate cable (untested) is available for AM.

The Terk HDR-I 'Indoor' AM/FM Active Antenna was tested by attaching it to the top a fiberglass pole and elevating it approximately nine feet above ground.

Figure 11 Terk HDR-I 'Indoor' AM/FM Active Antenna



Terk HDR-O AM/FM 'Outdoor' Active Antenna

This unit, which is marketed as supporting HD Radio reception, consisting of a tubular metal loop approximately sixteen inches in diameter with a plastic center section. Instructions suggest that it should be installed out-of-doors, although indoor mounting is clearly an option. It requires an external 12 VDC power source (which was supplied for the tests by a small lead-acid utility vehicle battery). Gain is fixed. Output is provided to a female F connector, and radio set end adapters are provide for powering and to separate the AM and FM outputs.

It was tested by attaching it to the top a fiberglass pole and elevating it approximately nine feet above ground.

Figure 12 Terk HDR-O "Outdoor" AM/FM Active Antenna